Fundamental concepts of metal forming technology

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1. Definitions and classification of Metal forming processes

1.1 Introduction:

Metal forming is a very important manufacturing operation. It enjoys industrial importance among various production operations due to its advantages such as cost effectiveness, enhanced mechanical properties, flexible operations, higher productivity, considerable material saving.

The objects and articles that we use in our daily life are man-made, engineered parts, which are obtained from some raw material through some manufacturing process. All these objects are made of a number of small components assembled into finished product. The pen that we use for writing, for example is made of several small parts, assembled together. An automobile is supposed to be an assembly of more than 15000 parts, produced through various manufacturing operations.

Manufacturing of finished parts and components from raw materials is one of the most important steps in production.

Production encompasses all types of manufacturing processes. Manufacturing refers to the conversion of raw materials into finished products employing suitable techniques. There are several methods of manufacturing such as metal casting, metal forming, metal machining, metaljoining and finishing.

Some of the modern methods of manufacturing include micro machining, nano fabrication, ultra precision manufacturing etc.

In order to fulfill the requirements of the ever-increasing demands of various types of industries, the manufacturing engineer has to choose the right type of material and the right type of equipment for manufacture so that the cost of production and the energy consumption are minimum.

The selection of suitable manufacturing process should also include concerns for environmental impacts such as air pollution, waste disposal etc.

Modern concepts such as lean manufacturing, adaptive control, agile manufacturing, group technology etc have considerable influence on cost reduction and quality improvements of products.

Computers and robots play important role in modern manufacturing techniques, today. Modeling and simulation of the process prior to mass production helps the manufacturing engineer fix up the best operating parameters and hence achieve the finished product to the utmost level of quality and cost-effectiveness.

The present course is focused on one of the important methods of manufacturing, namely, metal forming.

1.2 Metal forming – definition:

Materials are converted into finished products though different manufacturing processes. Manufacturing processes are classified into shaping [casting], forming, joining, and coating, dividing, machining and modifying material property.

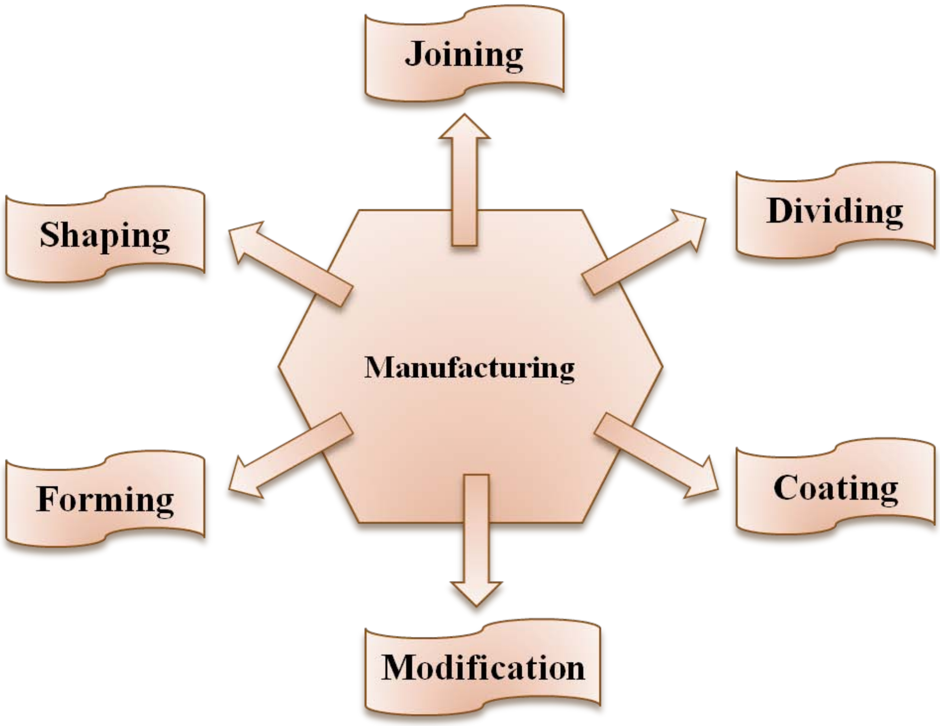


Fig.1.2.1: Various manufacturing operations on materials

Of these manufacturing processes, forming is a widely used process which finds applications in automotive, aerospace, defense and other industries.

Wrought forms of materials are produced through bulk or sheet forming operations. Cast products are made through shaping – molding and casting.

A typical automobile uses formed parts such as wheel rims, car body, valves, rolled shapes for chassis, stamped oil pan, etc.

In our daily life we use innumerable formed products e.g. cooking vessels, tooth paste containers, bicycle body, chains, tube fitting, fan blades etc.

Forming is the process of obtaining the required shape and size on the raw material by subjecting the material to plastic deformation through the application of tensile force, compressive force, bending or shear force or combinations of these forces.

1.3 Classification of forming:

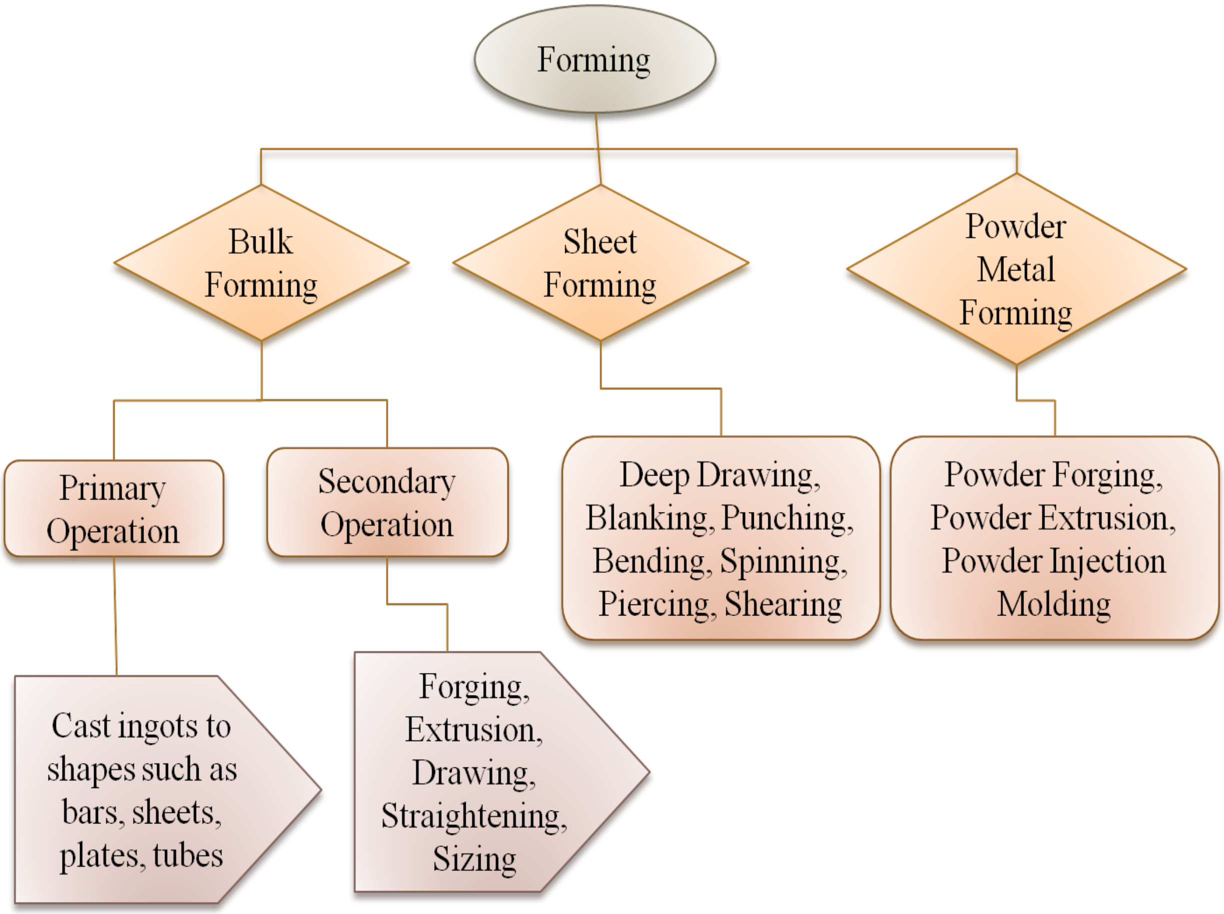


Fig. 1.3.1: Classification of metal forming processes

Typically, metal forming processes can be classified into two broad groups. One is bulk forming and the other is sheet metal forming. Bulk deformation refers to the use of raw materials for forming which have low surface area to volume ratio. Rolling, forging, extrusion and drawing are bulk forming processes. In bulk deformation processing methods, the nature of force applied may be compressive, compressive and tensile, shear or a combination of these forces.

Bulk forming is accomplished in forming presses with the help of a set of tool and die. Examples for products produced by bulk forming are: gears, bushed, valves, engine parts such as valves, connecting rods, hydraulic valves, etc.

Sheet metal forming involves application of tensile or shear forces predominantly. Working upon sheets, plates and strips mainly constitutes sheet forming. Sheet metal operations are mostly carried out in presses – hydraulic or pneumatic. A set of tools called die and punch are used for the sheet working operations. Bending, drawing, shearing, blanking, punching are some of the sheet metal operations.

A new class of forming process called powder forming is gaining importance due to its unique capabilities. One of the important merits of powder forming is its ability to produce parts very near to final dimensions with minimum material wastage. It is called near-net-shape forming. Material compositions can be adjusted to suit the desirable mechanical properties. Formability of sintered metals is greater than conventional wrought materials. However, the challenge in powder forming continues to be the complete elimination or near-complete elimination of porosity. Porosity reduces the strength, ductility and corrosion resistance and enhances the risk of premature failure of components.

Based on the nature of deformation force applied on the material, during forming, metal forming processes are also classified into several types as shown below:

Forming by compressive stress	Tensile and compressive stresses	Forming under Tensile stress	Bending and shearing stresses
•Open Die Forging •Closed Die Forging •Rolling •Coining •Extrusion	•Deep drawing •Spinning •Stripping •Wrinkle bulging	•Stretch forming •Stretching •Expanding	•Bending •Shearing •Punching •Blanking

Forming is also classified as cold forming, hot forming or warm forming. Hot forming is the deformation carried out at temperatures above recrystallization temperatures. Typically, recrystallization temperatures for materials ranges from 0.5 Tm to 0.8 Tm, where Tm is melting temperature of material.

1.4 Brief description of forming operations

We discuss briefly the various forming operations in the following sections.

1.4.1 Bulk forming processes:

Rolling is a compressive deformation process, which is used for producing semi-finished products such as bars, sheets, plates and finished products such as angles, channels, sections.Rolling can be carried out both in hot and cold conditions.

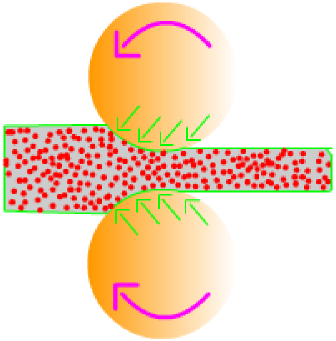
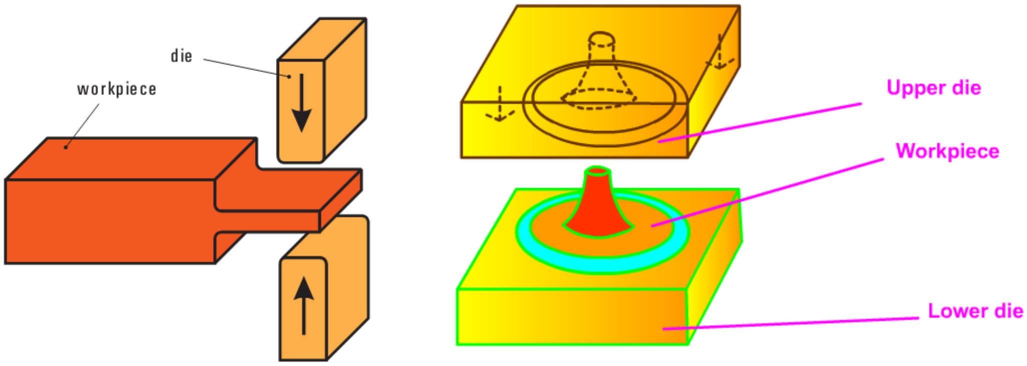


Fig.1.4.1.1:Rolling Process

Forging is a bulk forming process in which the work piece or billet is shaped into finished part by the application of compressive and tensile forces with the help of a pair of tools called die and punch. Forging can be done in open dies or closed dies. Open die forging is usually used for preliminary shaping of raw materials into a form suitable for subsequent forming or machining.



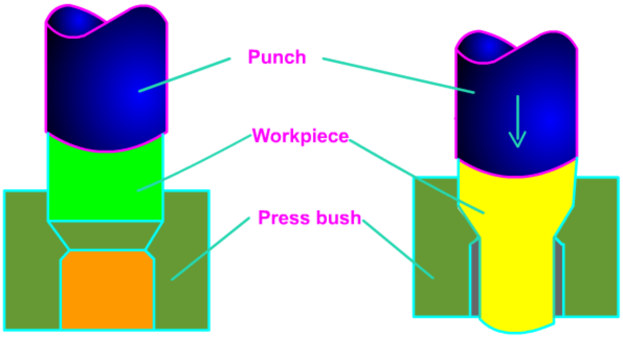
Open die forgingClosed die forming

Fig.1.4.1.2: Forging processes

Open die forming is done using a pair of flat faced dies for operations such as drawing out, thinning, etc.

Closed die forming is performed by squeezing the raw material called billet inside the cavity formed between a pair of shaped dies. Formed products attain the shape of the die cavity. Valve parts, pump parts, small gears, connecting rods, spanners, etc are produced by closed die forming.

Coining is the process of applying compressive stress on surface of the raw material in order to impart special shapes on to the surface from the embossing punch – e.g. coins, medallions



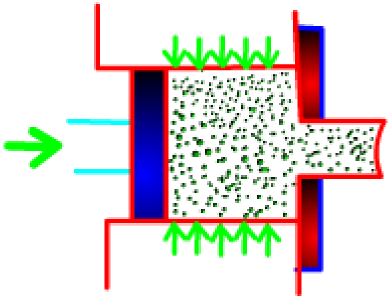


Fig.1.4.1.3:Direct extrusion process

Extrusion involves forcing the raw material through a narrow opening of constant cross-section or varying cross-section in order to reduce the diameter and increase the length. Extrusion can be done hot or cold. Extruded products include shafts, tubes, cans, cups, gears.

Basically there are two methods of extrusion, forward and backward extrusions. In forward extrusion the work and the extrusion punch move along the same direction. In backward extrusion the punch moves opposite to the direction of movement of the work piece.

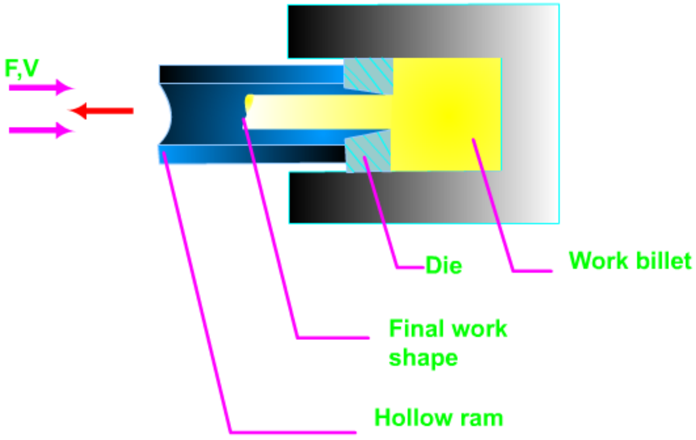


Fig.1.4.1.4:Backward extrusion or Indirect extrusion

Wire drawing process is used for producing small diameter wires from rods by reducing their diameter and stretching their length through the application of tensile force. Musical strings are produced by wire drawing process. Seamless tubes can be produced by tube drawing process.

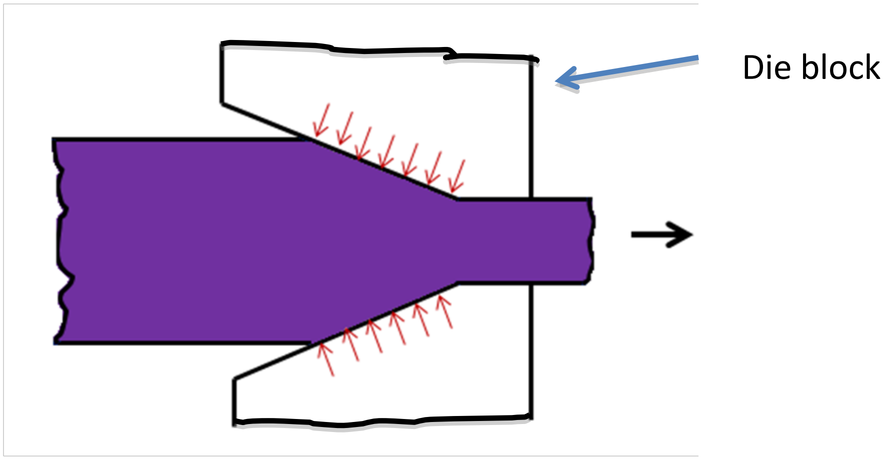


Fig.1.4.1.5:Wire Drawing

1.4. 2 Sheet metal operations:

Deep drawing is a sheet metal process the process in which a sheet metal is forced into cup of hollow shape without altering its thickness – using tensile and compressive forces. Complex shapes can be produced by deep drawing of blanks in stages – redrawing, multiple draw deep drawing etc.

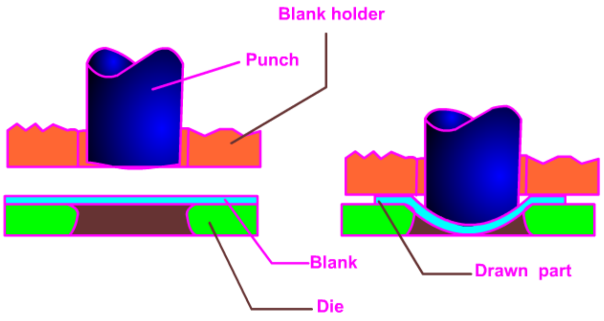


Fig.1.4.2.1:Deep drawing

Hydro mechanical deep drawing uses both punch force and hydrostatic force of a pressurized fluid for achieving the shape.

Flanges and collars are formed by flanging process.

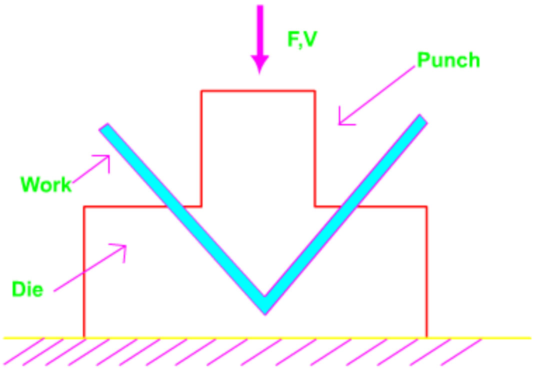
Spinning transforms a sheet metal into a hollow shape by compressive and tensile stresses. Spinning mandrel of given shape is used against a roll head.

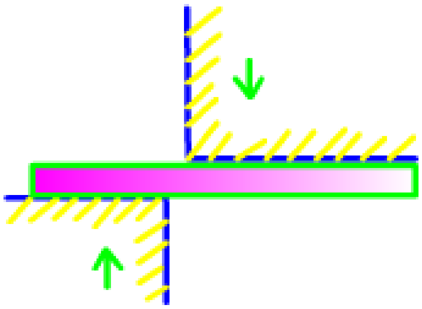
Embossing imparts an impression on the work piece by means of an embossing punch.

Bending of sheets includes rotary bending, swivel bending, roll bending using rotary die.

Die bending using flat die or shaped die is used for bending of sheets, or die coining of sheets.

Basic Sheet Metal Working Operations : Bending





Basic Sheet Metal Working Operations : Bending

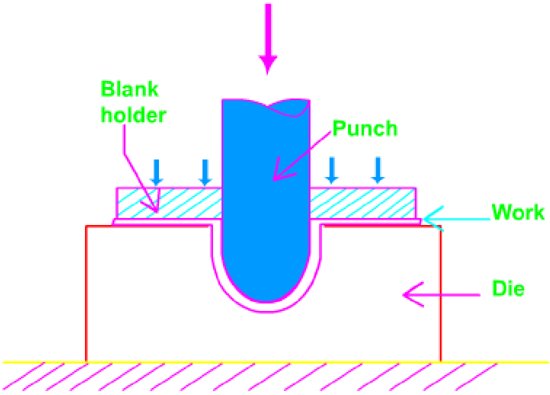


Fig.1.4.2.2:Bending and shearing

Materials and their structures

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2. Materials and their structures

2.1 Introduction:

The ability of materials to undergo forming by different techniques is dependent on their structure and properties. Behavior of materials depends on their structure-atomic structure, crystal structure and grain structure.

Materials are generally classified into metals/alloys and non-metals such as plastics, ceramics, composites. Metals are further classified into ferrous and nonferrous metals. Further, materials can be classified into crystalline and amorphous materials.

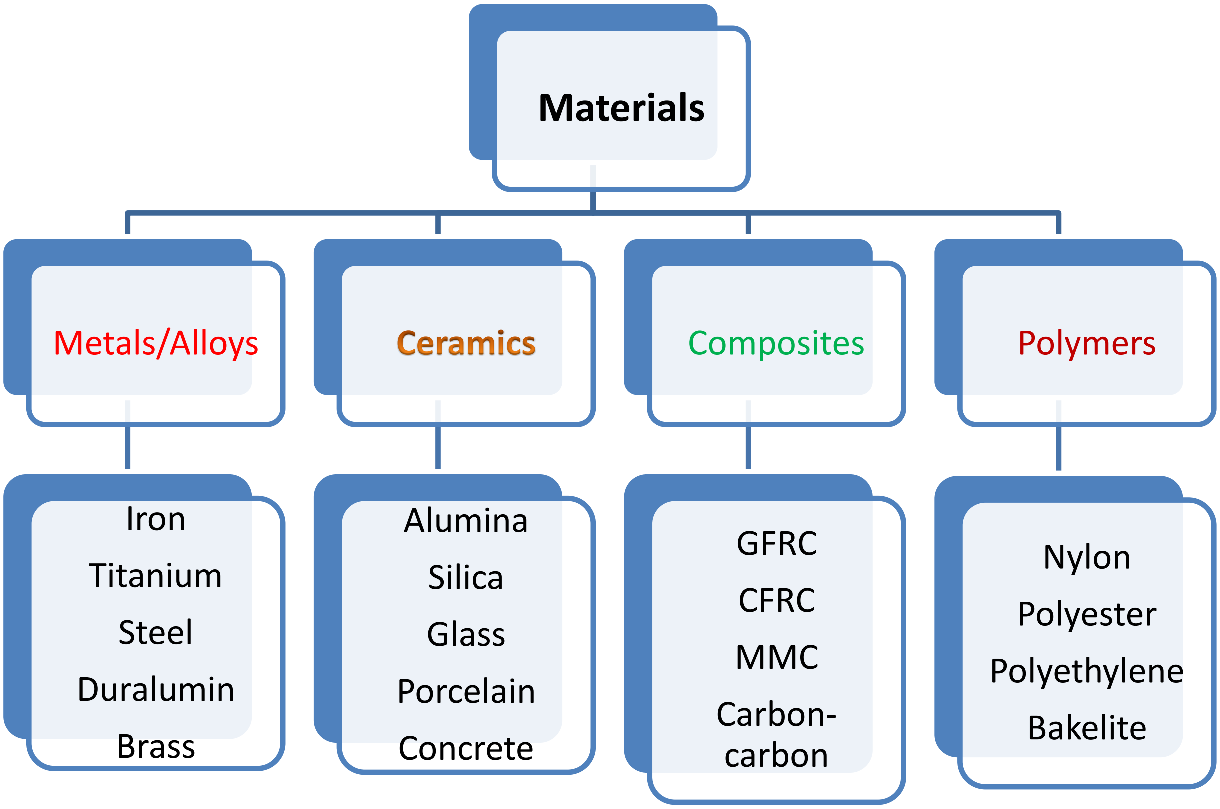

Fig. 2.1.1: Classification of materials

2.2 Crystalline arrangement:

Crystalline materials have atoms arranged symmetrically in long range order. In amorphous materials there is short range order, the orderly arrangement of atoms being discontinuous.

Crystalline solids have their atoms arranged in three dimensional space in basic forms called lattices – Bravais lattices.

There are basically 7 lattice systems, namely, Cubic, hexagonal, tetragonal, orthorhombic, rhombohedral, monoclinic, triclinic.

Crystal structures of commonly used engineering metals and alloys can be grouped into three types, namely, body centered cubic [BCC], face centered cubic [FCC] and hexagonal closed pack [HCP]. The smallest group of stacked atoms which repeats itself in three dimensional space and hence fixes the lattice structure can be defined as unit cell.

Physical and mechanical characteristics of crystalline solids are dependent on the effective number of atoms in a unit cell, density and orientation of packing of atoms within the unit cell.

Unit cells are represented by hard-ball models. The effective number of atoms in a unit cell represents the extent of packing of atoms and void space within the unit cell.

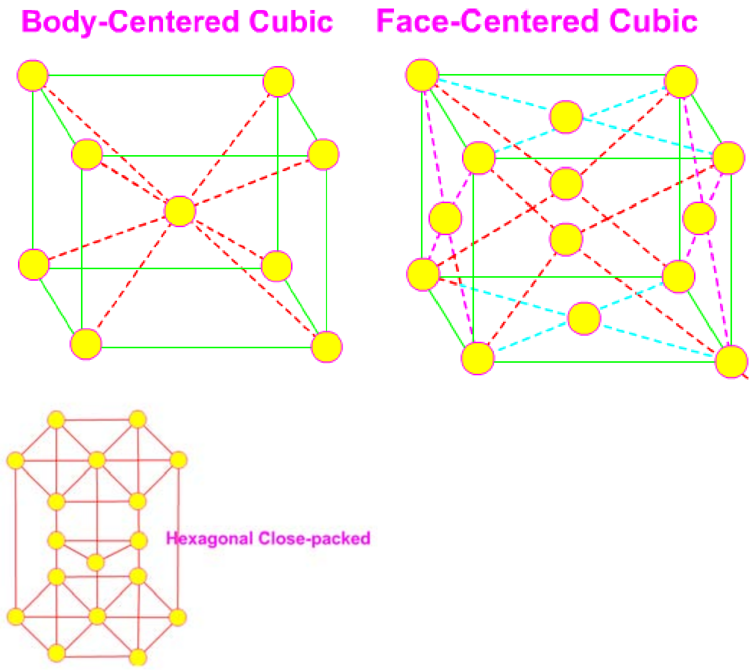

Fig. 2.2.1: Unit cell structures of Cubic and HCP lattices

BCC: Metals like alpha iron, chromium, molybdenum, tungsten, vanadium exhibit BCC structure. The packing efficiency which is the ration of the volume of effective number of atoms per unit cell to the volume of the unit cell for BCC is found to be 58%.

Number of neighboring atoms in a BCC unit cell is 8 – called coordination number.

FCC: Metals like nickel, copper, aluminium, silver, gold, platinum have fcc structure with a packing efficiency of 74%. And coordination number of 12.

HCP: For hcp metals such as zinc, magnesium, alpha titanium, cobalt, cadmium the packing efficiency is 74% and coordination number is 12.

FCC and HCP have more densely arrangement of atoms within, than BCC.

2.3 Planar and direction indices

Mechanical properties of crystalline materials such as ductility, strength etc are also dependent on the directions and planes of close packing of atoms. Atomic planes and atomic directions in unit cells are represented by Miller indices and Miller Bravais indices, respectively.

Closely packed directions and planes determine the nature of deformation in crystalline objects.Miller indices are represented as <abc> and Bravais indices are represented as {xyz}. Miller indices are the reciprocal of the intercepts of the atomic plane with the three coordinate axes, rounded off to nearest whole number. Miller indices of direction are the intercepts of atomic direction with the three coordinate axes.

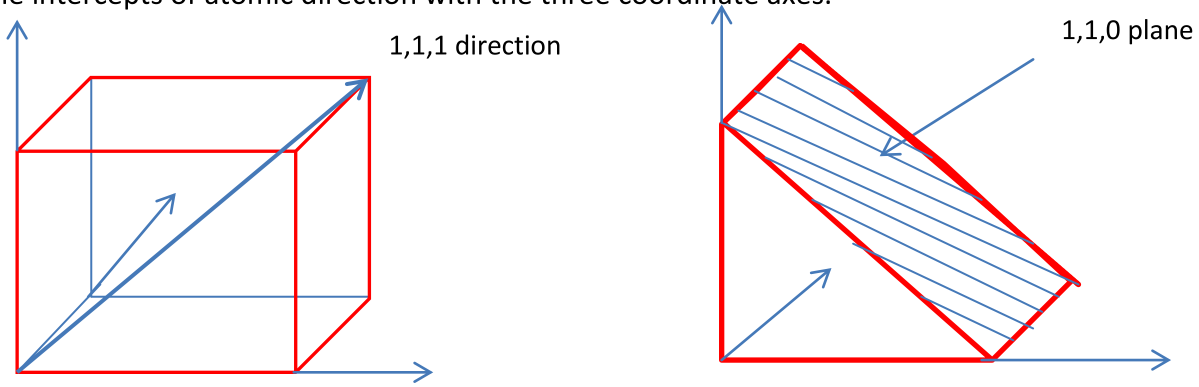

Fig. 2.3.1:Miller indices of direction and plane

Miller indices of atomic directions are obtained as the difference between the intercepts of the end point of the direction and origin of the direction with the respective reference axes.

Difference in crystal structures of metals is due to the difference in energy required for the formation of the structures among different atoms. Some metals can exist in different crystal structures under different conditions of temperature. Iron exists as BCC at room temperature, but when heated to 1185 K it becomes FCC. This property is called polymorphism or allotropism.

Adding another element to a pure metal forms an alloy. For example carbon added to iron forms steel which has different properties compared to iron.

Alloying generally improvesstrength and hardness of pure metals. Pure metals as such have limited engineering applications in view of their limited strength, hardness, wear resistance, fatigue and creep resistance.

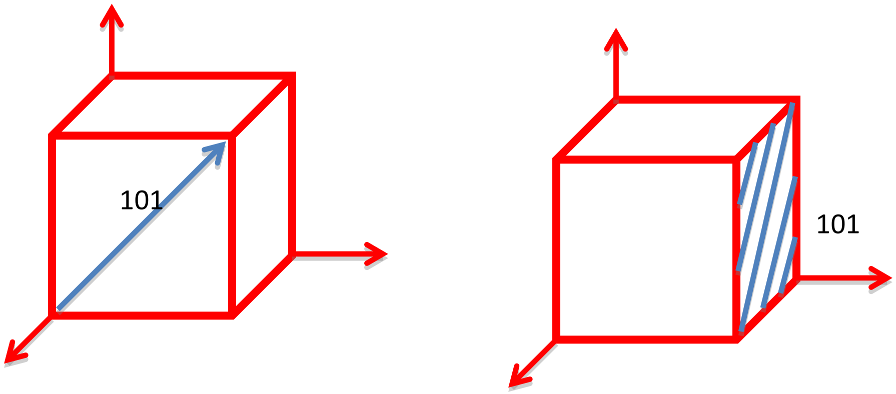

Fig. 2.3.2: 101 direction and 101 plane in cubic lattice

2.4 Crystal imperfections:

Crystal structures are never perfect – there are defects in the arrangements of atoms in crystalline materials. Imperfections arise during solidification of crystalline materials, or they may occur during processing of materials like mechanical deformation. Adding alloying element is a deliberately introduced imperfection.

There are generally three kinds of defects, namely, point defects, line defects and surface defects.

Vacancy – missing of an atom from the lattice position. It can happen due to nuclear irradiation of a material.

Interstitialcy – presence of an additional atom in the interstitial space.

Frenkel defect – Ion removed from its regular position and moved to interstitial position.

Schottky defect – missing pair of ions of opposite charge.

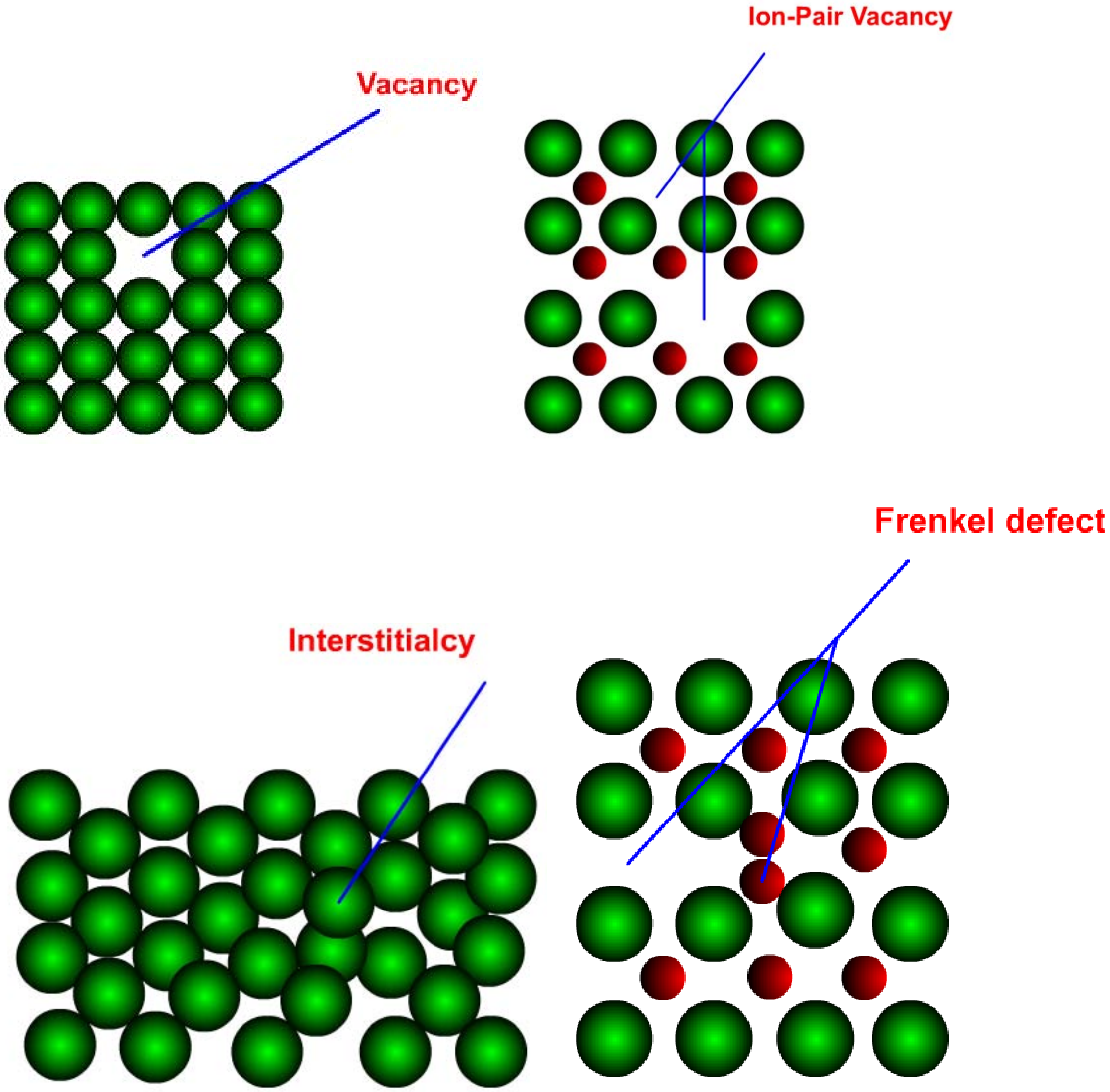

Fig. 2.4.1: Point imperfections

Line defects – these are collection of point defects. There are two types of line defects – edge and screw dislocations.

Edge dislocation – extra plane of atoms present within the crystal – giving raise to distortion of the structure.

Screw dislocation – It is a kind of distortion in the arrangement of atoms produced by a shear between two halves of a crystal – the upper front part moved by one atomic distance with reference to lower front.

Unit displacement of atoms in dislocations is represented by the Burgers vector.

Dislocations play active role during plastic deformation of crystalline solids.

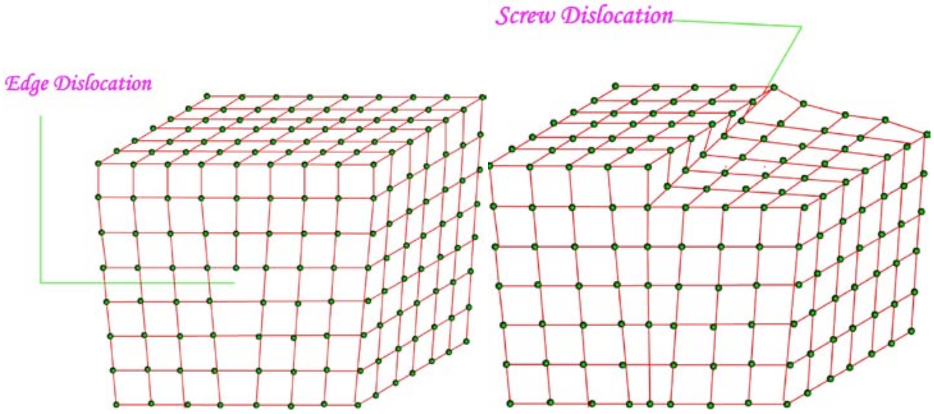

Fig. 2.4.2: Line defects-dislocations

Surface defects – grain boundaries in polycrystalline materials – which are orientation mismatch between adjacent grains. Grain boundaries are high energy regions and are amorphous. For large grains, the interfacial energy is lower due to lower interfacial area compared to small grains. At elevated temperatures, grains become larger in order to reduce the interfacial energy.

In single crystals there are no grain boundaries – therefore single crystals are stronger.

2.5 Deformation of crystalline solids:

2.5.1 Single crystals:

Application of external force on a crystalline solid results in distortion of the lattice structure. If the applied force is small, the distortion called elastic deformation can take place. At the removal of the force, the crystal structure comes to original shape.

If the applied force exceeds a certain limit, the deformation undergone by the solid is called plastic deformation – as the deformation remains even after removal of load or force.

Permanent deformation is called plastic deformation.

Maximum theoretical shear strength of a perfect crystal – stress causing plastic deformation – is given to be:

$$\tau = G/2\pi$$

where G is shear yield strength of the material.

Similarly, it can be shown that the maximum theoretical tensile strength of a perfect crystalline solid is given by:

$$\sigma = E/10$$

where E is elastic modulus. Theoretical strength is of the order of GPa.

However, actual shear strength and tensile strength of crystals is much less than that predicted by the above expressions because of crystal defects discussed in sections above.

2.5.2 Polycrystalline materials

Polycrystalline materials have defects in the crystal structure, which considerably reduce their strength.

Basic mechanisms causing plastic deformation in crystalline solids are slip and twinning.

Slip is sliding of one plane of atoms over another plane due to application of force-shear force. It is similar to the sliding of playing cards. A minimum shear stress called critical resolved shear stress is required to cause slip in single crystals. Slip specifically happens only along specific planes called slip planes and along specific directions called slip directions. Family of slip planes and slip directions together form slip systems.

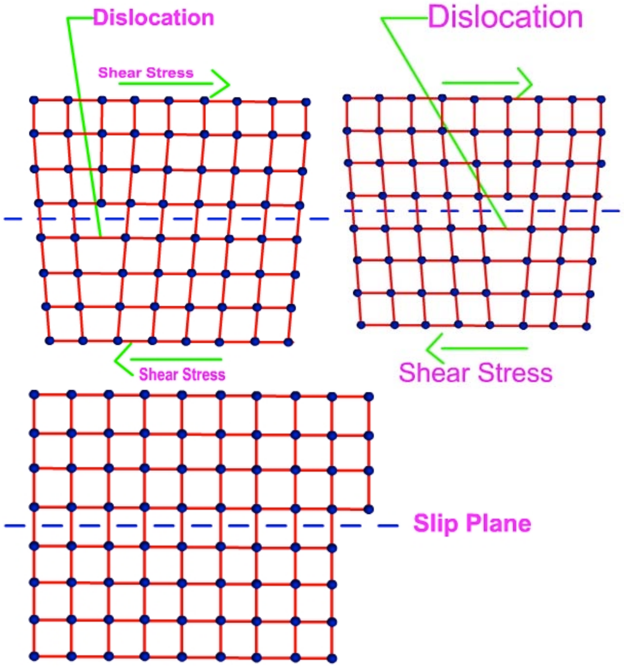

Fig. 2.5.2.1: Dislocation motion by slip

Different crystals have different slip systems. For example, for FCC structured metals, there are 12 slip systems, and for BCC metals there are 48 slip systems. However, out of 48 slip systems only some are active. BCC metals have higher strength than FCC metals generally.

Slip always happens along planes of maximum atomic density.

Less number of slip systems in HCP – only three – makes materials with HCP more brittle.

Slip is also caused by the movement of edge and screw dislocations in materials. Movement of an edge dislocation can be analogous to the motion of a caterpillar.

In single crystals, the magnitude of slip produced is dependent on the magnitude of shear stress induced by the external stress acting on the material. Slip begins when the shear stress reaches a critical value called critical resolver shear stress (CRSS). This principle is called Schmid's law. It is shown that this stress, CRSS is equal to:

CRSS = $\boldsymbol{\sigma \cos\theta\cos\Phi}$

Where σ is the tensile stress applied on the crystal, θ is angle between normal to slip plane and axis of the tensile stress, Φ is angle between slip direction and the tensile axis.

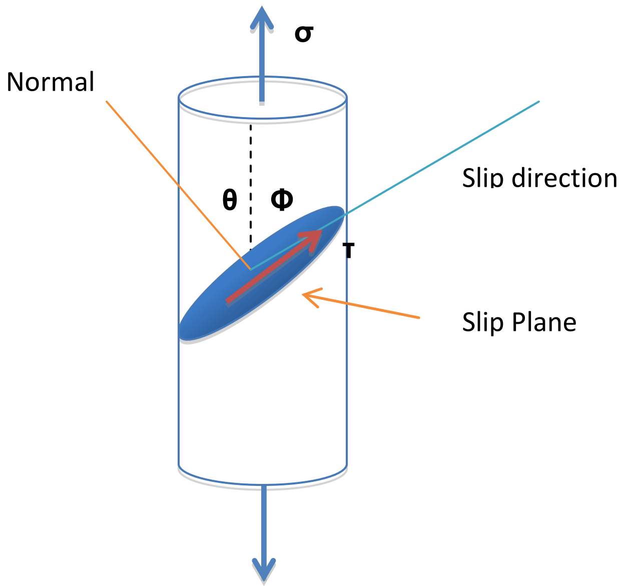

Fig. 2.5.2.2: Critical resolved shear stress

CRSS is a material property which depends on the type of structure and temperature.

For iron, the CRSS value is given at room temperature as 27.5 MPa, for nickel it is 5.7 MPa, for zinc it is 0.18. As seen here, Zn being hcp, has low CRSS. Alloying can increase the critical resolved shear stress. If there are more dislocations, impurities, solutes, the CRSS value of the metal increases, due to increased resistance to dislocation movement.

Twinning is the other mechanism of plastic deformation. Twinned structure is a mirror image of atoms across a plane of twinning. In HCP and bcc materials twinning may take place causing cracking sound during failure.

Plastic deformation of crystalline solids causes an increase in dislocation population. Dislocation density – defined as total length of dislocation per unit volume in cold-worked materials can be as high as 10^{12}.

Dislocation entanglements and obstruction to slip movement of dislocations during deformation can cause increase in strength of a metal. This is called strain hardening or work hardening.

Deformation in polycrystalline materials – grains of almost equal size are called equiaxed grains. Finer grains are formed during rapid cooling of molten metal. Higher the cooling rate finer the grain size.

Finer grains prevent easy motion of dislocations thereby increasing the strength of crystalline materials.

Single crystal has anisotropic properties, whereas polycrystalline materials have isotropic properties. Isotropy refers to uniform properties along all directions in the crystal.

Grain size has profound effect on strength and hardness of metals. Large grains produce smaller strength. Yield strength dependence on grain size is given by Hall-Petch relation:

$$\mathbf{Y = Y_i + kd^{-1/2}}$$

where Y_i is resistance to dislocation motion, d is grain size, k is a constant indicating dislocation pileup.

Grain size is given by ASTM grain size number, n.

$N = 2^{n-1}$, where N is number of grains per square inch at a magnification of 100X and n is grain size number-varies between 0 and 10.

Mechanical behavior of crystalline materials-1

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3.1 Mechanical behavior of crystalline materials

3.1 Introduction

Engineering materials are often found to posses good mechanical properties so then they are suitable for applications. Mechanical properties referred here are tensile strength, ductility, toughness, fatigue strength, hardness etc. Ductility is estimated from uniaxial tensile test. Percentage reduction in area obtained from uniaxial tensile test is taken to be a measure of ductility. In this lecture, we will focus on tensile behavior of materials.

Metallic materials have good ductility. They are easily deformable by application of external forces. Formability, the ease with which metals and alloys can be plastically deformed to a required shape depends on the nature of structure, grain structure and types of metallurgical phases that make a given alloy. For example a hardened steel which has a martensitic structure is impossible to shape.

Forming of materials can be achieved through plastic deformation of the material by applying stress. Therefore, it is important to understand the plastic deformation behavior of materials. Material behavior under three different types of loading, tensile, compressive and torsion loading will be discussed in the following sections.

3.2 Stresses – types:

Suppose a certain force ΔF is acting on an area ΔA. Then the stress acting along an arbitrary direction is given as $\lim_{\Delta A \to 0} \frac{\Delta P}{\Delta A} = \sigma$

This stress can be resolved along a direction perpendicular to the given surface called normal stress, σ.

It is resolved along tangential direction to the given surface, called shear stress, τ.

Normal stress can produce both normal and shear strains in a material. Shear stress produces shear strain. Normal Strain is the change in length divided by original length. Shear strain is the angular change of a right angle edge of the solid.

3.3 Tensile behavior:

3.3.1: The uniaxial tension test

Tension test is a simple test used for finding the strength of materials. A round rod specimen, gripped on ends and is subjected to increasing axial load. The stress applied is measured using load cell. Strain on the specimen is measured using extensometer. A metallic material, when loaded in tension, initially deforms elastically. Elastic deformation refers to material strain which can be recovered fully. In elastic deformation, the nominal stress which is the load applied divided by the initial area of cross section of the rod, increases linearly with strain.

Engineering strain is defined as change in length divided by initial gage length. True strain is defined as change in length divided by instantaneous gage length.

Engineering stress or nominal stress is the load applied divided by initial cross section area of the rod.

In the elastic region, the linear stress – strain relation is given by Hooke's law:

$$\sigma = \boldsymbol{\varepsilon} E$$

The modulus of elasticity, E is a material property, which depends on the nature of bonding in a material. Typical value of E for steels is in the range 190 – 200 GPa, whereas for aluminium, it ranges from 69 to 79 GPa.

Elastic Poisson ratio is defined as ratio of linear [elongation] strain to lateral strain[contraction]. Poisson's ratio for steels ranges from 0.28 to 0.33. Maximum value of Poisson's ratio is 0.

Typical stress-strain curves for ductile materialswith pronounced yielding and without yielding shown below:

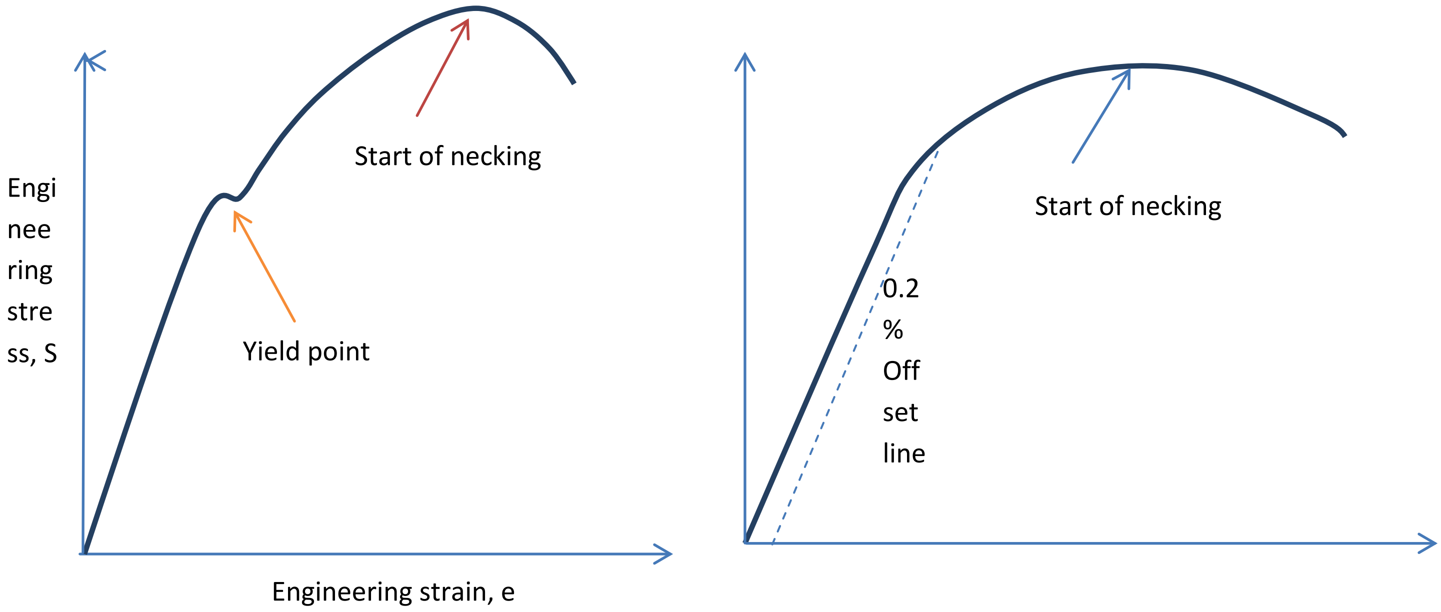


Fig. 3.3.1.1: Engineering and true stress-strain curves for a ductile material

From the tensile curve on can find many properties of the material. Beyond the elastic limit (linear), the material behavior is said to be plastic. The deformation in plastic behavior is permanent. Plastic deformation commences after elastic deformation, which is represented in stress-strain diagram by yielding. Some materials do not show yielding – materials such as copper.

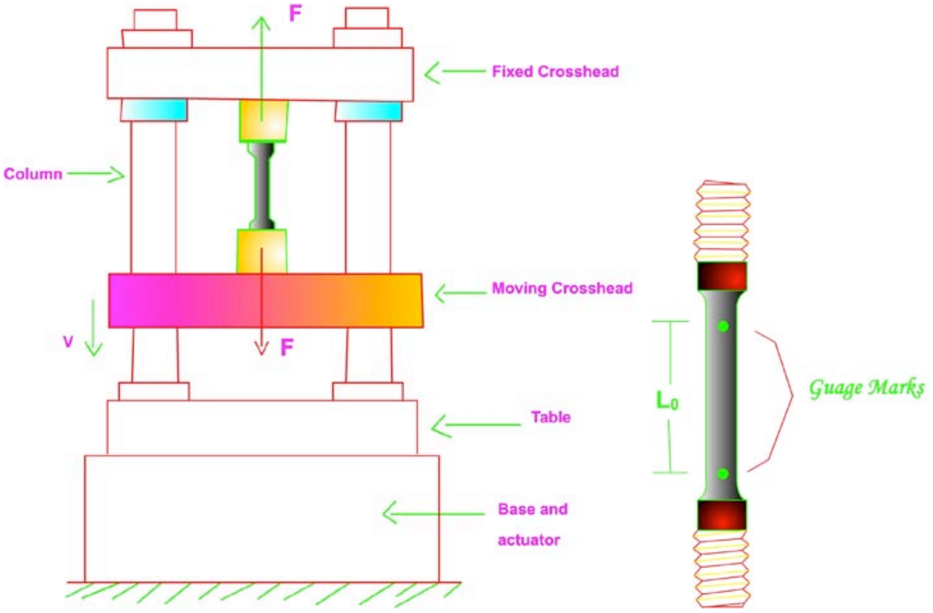


Fig. 3.3.1.2: Tensile test setup and tensile specimen

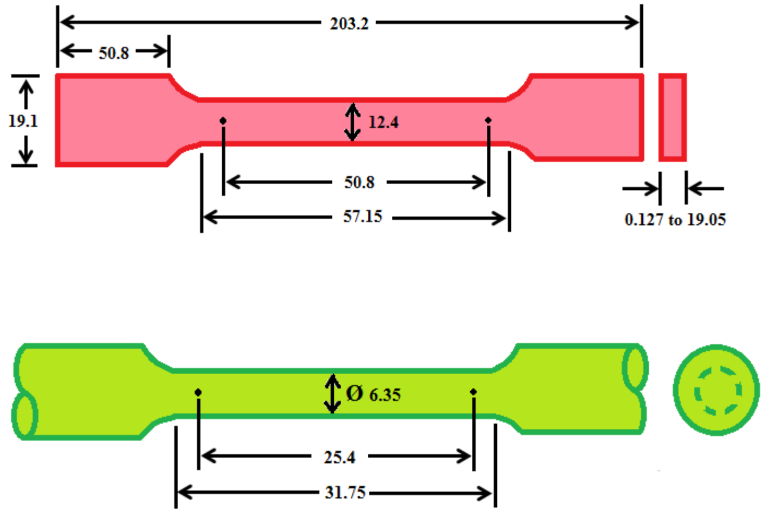


Fig. 3.3.1.3: Standard (ASTM E8) Tensile Specimens of plate and cylindrical types

The stress at yield point is called yield strength. In case of materials which do not show pronounced yielding, the yield point strength is defined by 0.2% proof strength. This is obtained by 0.2% offset on the strain.

Yield point stress is important in case of metal forming operations, because, forming processes require the metal to deform plastically.

The area under the stress-strain curve upto yielding is called Modulus of resilience [MR].

MR = $Y^2/2E$, Y being the yield strength. Springs should have high modulus of resilience, so that they can absorb more energy during elastic deformation and store it.

The plastic portion of the stress-strain curve is non-linear. As the specimen gets loaded beyond yield point, the curve reaches a maximum. The stress corresponding to this maximum point – known as ultimate tensile strength [UTS].

UTS = F_{max}/A_o

Until this point there is uniform reduction in area of cross section of the specimen. After the point of maximum engineering stress, with continued loading, the specimen forms a neck – which has low area of cross-section – due to concentration of stress locally. Necking is localized deformation. After necking begins, the deformation is restricted to necked region alone.

With further loading, the engineering stress drops beyond necking point, till the point of fracture. Fracture essentially occurs at the necked region, due to triaxial state of stress in the neck region. Also because the material cross-section in the neck region is very small. The strain at the point of fracture is called total strain.

Some of the useful mechanical properties of the material, which is being subjected to tensile loading, that can be evaluated from the stress-strain behaviour are: a] Yield strength, b] Ultimate strength, c] Percentage elongation and percentage area reduction.

Ductility of a material is defined as percentage elongation or percentage reduction in area of cross-section. The percent elongation is defined as $[l_f-l_o]/l_o$, and the percentage reduction in area = $[A_o-A_f]/A_o$ X 100.

For metals, elongation may range from 10% to 60% and reduction in area may range from 20% to 90%. For some metals tensile properties are listed below:

Table 3.3.1.1: Tensile properties of some alloys

Material	Yield strength, MPa	Tensile strength, MPa	% Elongation
Low carbon steel	175	300	30
Annealed aluminium	28	69	40
Cold worked aluminium	105	125	8
Alloy steels	500	700	20
Austenitic stainless steel	275	650	55

True stress is defined as ratio of load applied to instantaneous cross-section area, $\sigma = P/A$. True strain is defined as change in gage length divided by instantaneous gage length. It is given as:

$$\varepsilon = \int dl/l = \ln(l/l_o) = 2\ln[D_o/D].$$

For small strains, we can take both engineering and trues strains to be equal. However, true strains are more consistent with real phenomena. Advantage of using true strain is apparent from the fact that total true strain is equal to sum of incremental true strains. Moreover, volume strain can be given as sum of the three normal true strains. True strains for equivalent amount of tensile and compressive deformations are equal, only differing in sign.

True stress and engineering stress are related by the expression:

$\sigma = S(1+e)$, where S is engineering stress, e is engineering strain.

Similarly, relation between engineering strain e and true strain ε is given as:

$$\varepsilon = \ln(1+e)$$

True strain is what happens naturally.

Flow stress:Metal forming operations involve plastic deformation of materials. The stress required to sustain a given amount of plastic deformation (plastic strain) is called flow stress. Flow stress is an important parameter in forming. It depends on type of material, temperature of working, conditions of friction at workpiece – tool interface, tool and work piece geometry etc.

3.3.2 True stress – true strain curve:

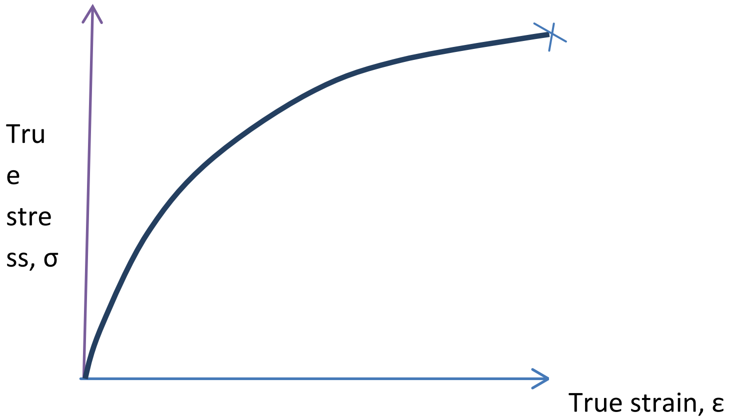


Fig. 3.3.2.1: True stress- true strain curve

True stress-strain curve does not indicate any yield point. It also does not show the elastic region.

The total area under the true stress-strain curve is known as toughness.

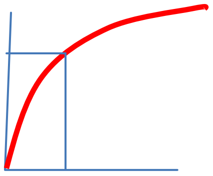
Toughness = $\int_0^{\varepsilon} \sigma d\varepsilon$, where ε is the fracture strain.

The true stress – true strain relation in the plastic portion is given by the power law expression:

$$\sigma = k\varepsilon^n$$

where k is strength coefficient, n is called strain hardening exponent.

Stress required,σ in plastic range to maintain plastic deformation at a certain strain, ε is called **flow stress**.



When the true stress is plotted against true strain on log-log plane, the power law relation, becomes a straight line. Slope of the line is n. n is called strain hardening exponent.

K, the strength coefficient is the value of stress σ, under ε=1.

During plastic deformation, as the ultimate strength is reached, the localized deformation called necking begins. This is called point of instability, as the specimen is no longer able to support the load. It can be shown that at the point of instability, n = ε_u, where ε_u is strain at ultimate point. At the neck, triaxial state of stress is known to exist, due to larger area reduction. Axial stress varies across the specimen in the neck region

Necking begins when the true strain is equal to the strain hardening exponent.

That is $n = \varepsilon$

Higher the value of n, higher the strain the material can withstand before necking.

During instability, the material becomes stronger due to strain hardening. However, the localized reduction in area makes the specimen less capable of bearing the load. The rate of decrease in area is more than rate of increase in strength due to strain hardening, thereby leading to instability. This is called geometric softening.

Instability due to necking may pose problems during forming of sheet metals.

3.3.3: Different types of stress-strain curves:

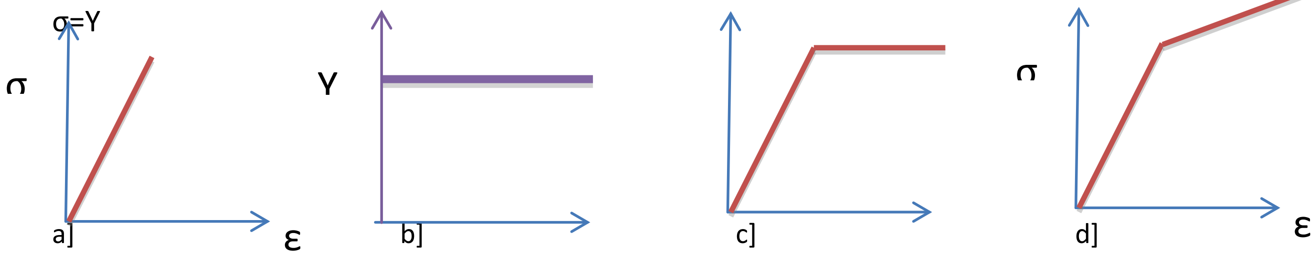


Fig. 3.3.3.1: Stress-strain behavior of different types of materials

Perfectly elastic: Figure – a, Brittle materials such as glass, ceramics, cast irons etc show only perfectly elastic behavior. There is very negligible yielding. Hooke's law governs the stress-strain relation. Stiffness of such material is indicated by E.

Rigid plastic, figure b – has infinite value of E, Once stress level reaches yielding Y, it continues to deform at same stress level.

Elastic, perfectly plastic-fugure c - is combination of perfectly elastic and rigid plastic. This material will undergo elastic recovery upon unloading. Metals heated to high temperature behave this way. Lead has elastic, perfectly plastic at room temperature.

Elastic, linearly strain hardening material, figure d – It approximates many of engineering materials. Such material has linear elastic behavior and linear plastic behavior. Due to strain hardening, the flow stress increases with increasing strain.

3.3.4 Factors affecting the stress-strain behavior

Temperature and strain rate influence greatly the stress-strain behavior of materials. Increasing the temperature reduces the tensile strength, yield strength, increases ductility.

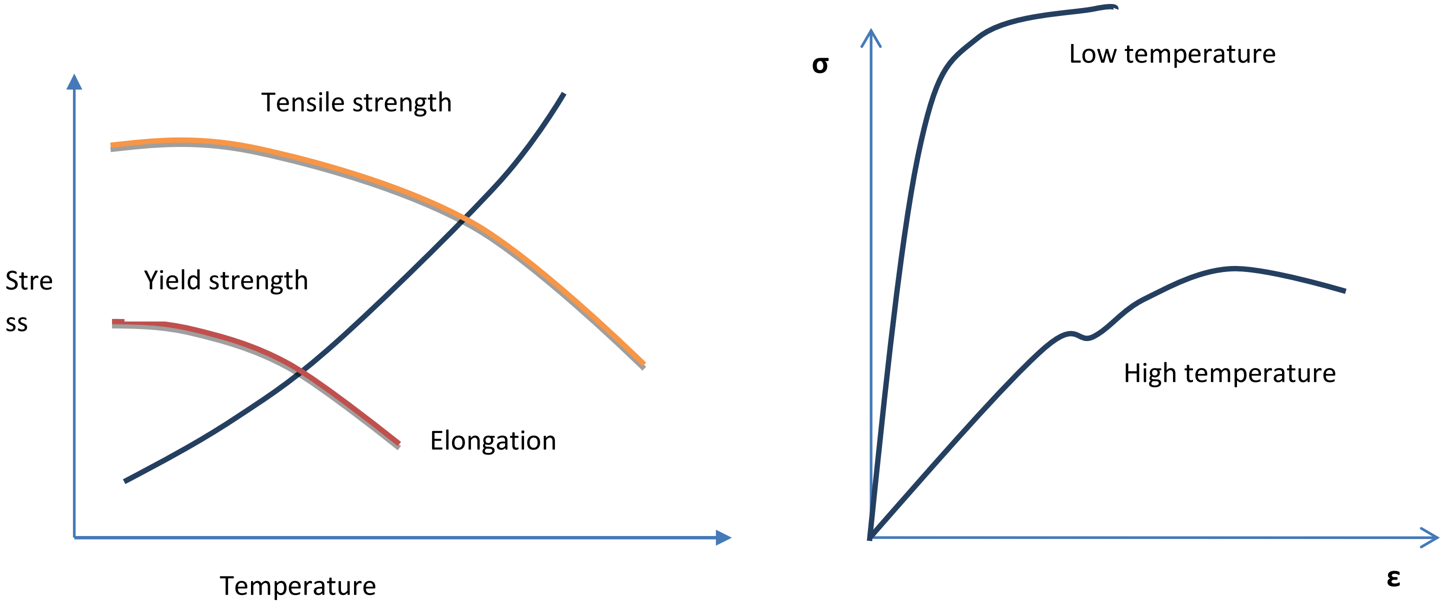


Fig. 3.3.4.1: Effect of temperature on mechanical properties and stress-strain behaviour

3.3.4.1 Strain rate effect

Strain rate is the rate at which material gets strained. Strain rate is expressed in s^{-1}.

Deformation speed of material in a process of forming is expressed in m/s.

Engineering strain rate is defined as $\dot{e} = \frac{de}{dT} = \frac{dl}{l_o\,dT} = \frac{v}{l_o}$, where v is velocity or deformation speed of the process, l_o is initial length. V is ram speed in tensile testing.

True strain rate is $\dot{\varepsilon} = \frac{v}{l}$

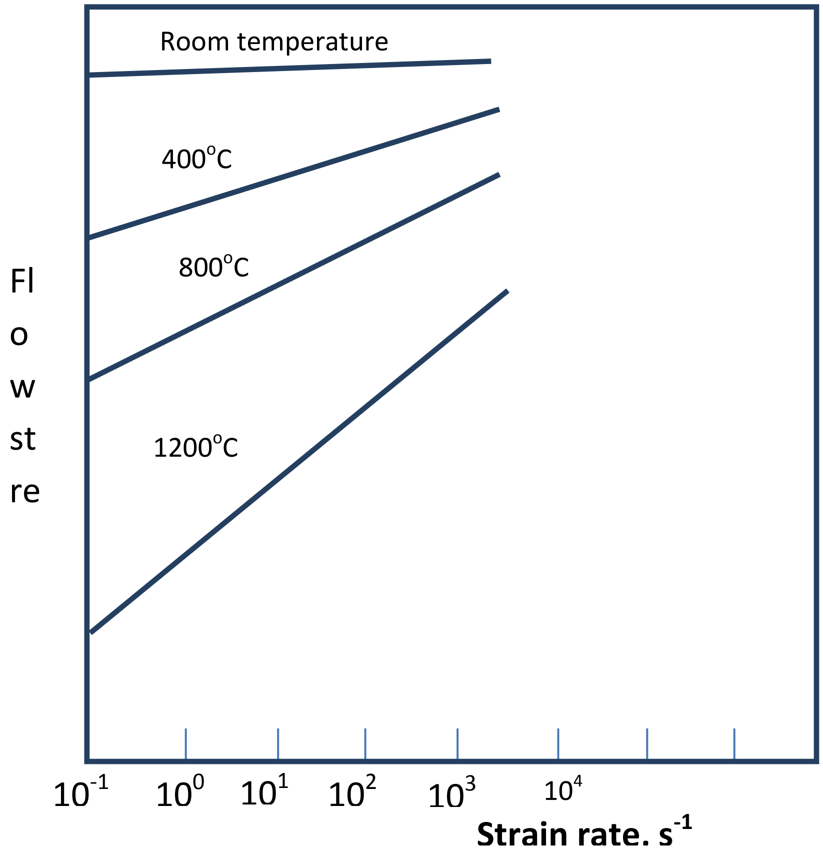
True strain rateis dependent on velocity and instantaneous length.

In order to maintain constant strain rate during tensile test, velocity of the cross head of the tensile machine has to be increased.

Increasing the strain rate increases the tensile strength. Increasing the temperature reduces the strength.

At higher temperatures, the sensitivity of strength to strain rate increases – strength becomes more sensitive to changes in strain rate. This is shown in figure below:

The flow stress is strongly dependent on strain rate at elevated temperatures.



Fir. 3.3.4.1.1: Variation of flow stress with temperature and strain rate

Velocity of deformation and strain rate of deformation during forming operations are deciding factors for selection of forming process and forming press. There are forming processes which are carried out at high strain rates and high velocities. Such processes are called high velocity forming. Example is explosive forming.

Strain rate and deformation velocity for some of the forming operations are given in table below:

Table 3.3.4.1.1: Strain rates and velocities in some forming operations

Process	True strain	Deformation speed, m/s	Strain rate, s^{-1}
Cold forging, rolling	0.1 – 0.5	0.1 - 100	$1 - 10^3$
Cold wire drawing	0.05 – 0.5	0.1 - 100	$1 - 10^4$
Hot forging, rolling	0.1 – 0.5	0.1 - 30	$1 - 10^3$
Hot extrusion	2 - 5	0.1 - 1	$10^{-1} - 10^2$
Sheet metal forming	1 - 10	0.05 - 2	$1 - 10^2$

Strain rate dependence of flow stress or tensile strength, can be represented by the expression:$\sigma = C(\varepsilon^{\dot{m}})^{\cdot}$, m is strain rate sensitivity parameter and $\dot{\varepsilon}$ is strain rate.

In general, the value of m decreases as strength increases.

With higher values of m, a material can undergo more plastic deformation before necking or failure.

The material near the necking becomes stronger due to work hardening, at the instance of necking. Strain rates near necking are also high. As a result, Necking gets delayed. There is large uniform deformation before failure.Elongation after necking also increases due to large values of m.

Superplastic behavior of some materials is possible only if the strain rate sensitivity for a material is high – 0.3 to 0. 85

Superplastic behavior is the ability of materials to undergo very large amounts of elongations – upto 1000% elongation, before failure. There is also no necking in such behavior as m values are high. Examples are thermoplastics, hot glass, fine grained titanium alloy, zinc-aluminium alloy.

Strain rate also affects the strain hardening exponent of materials. Strain hardening exponent decreases with increase in strain rate.

Generally ductility of materials is dependent on strain rate sensitivity parameter, m.

3.3.4.2 Hydrostatic stress:

Hydrostatic stress refers to a state of stress in which the stress acting along all the three directions is the same and of the same sign. Hydrostatic stress cannot cause yielding of conventional materials, because the plastic deformation of crystalline materials is caused by mechanism of slip. Slip is essentially caused by shear force.

Hydrostatic stressis found to influence the plastic deformation process by affecting material property. Hydrostatic stress leads to increase in ductility of a material. Hydrostatic stress increases true fracture strain. However, it has no effect on necking, maximum stress, strain. Hydrostatic stress is found to increase the ductility of brittle materials like cast iron, ceramics.

In metal forming operations, large strains are involved, true strains exceeding 3 to 4.

Therefore, simple tensile test and the results obtained from the same are not sufficient to predict the flow stress of materials. Homogeneous compression test, torsion test, plane strain compression test are some of the tests which are used for determination of the flow stress. These tests are discussed in next lecture.

Mechanical behavior of crystalline materials-2

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4. Mechanical behavior of crystalline materials-2

In the previous lecture we have considered the behavior of engineering materials under uniaxial tensile loading. In this lecture we will discuss material behavior during compression and shear. The main focus is with reference to metal forming processes. Further, material properties such as hardness and toughness are dealt with.

4.1 Compressive behavior:

Many bulk forming operations involve compressive stress. Therefore, it is important to study the material behavior under compression. Moreover, the simple compression test is utilized for determination of material flow stress.

4.1.1 Simple axial compression:

In simple compression test, a cylindrical billet held between two platens, is subjected to compressive stress. Friction at interface causes non-uniform flow along the height of the billet, causing barreling. Compression test can be used for determination of ductility and fracture limit. Large strains can be induced in compression test without necking.

The simple homogeneous compression test can be used for determination of flow stress of a material. A cylindrical piece of initial height to diameter ratio Ho/Do is subjected to compression between two platens, applying the load incrementally. True strain is calculated from the formula:

$\varepsilon = \ln(H_o/H)$, where H is deformed height. True stress can be calculated from:

$\sigma = F/\pi R^2$R is instantaneous radius of billet, F is the force applied axially on billet

The height to diameter ratio of the billet should not exceed 2 in order to avoid bucking. Also a very low value of H_o/D_o will make the deformation more difficult and higher loads are required due to the presence of un-deformed zones.

Strain in compression test is given as:

$e = [h_o - h]/h_o$, h being height of billet at any load.

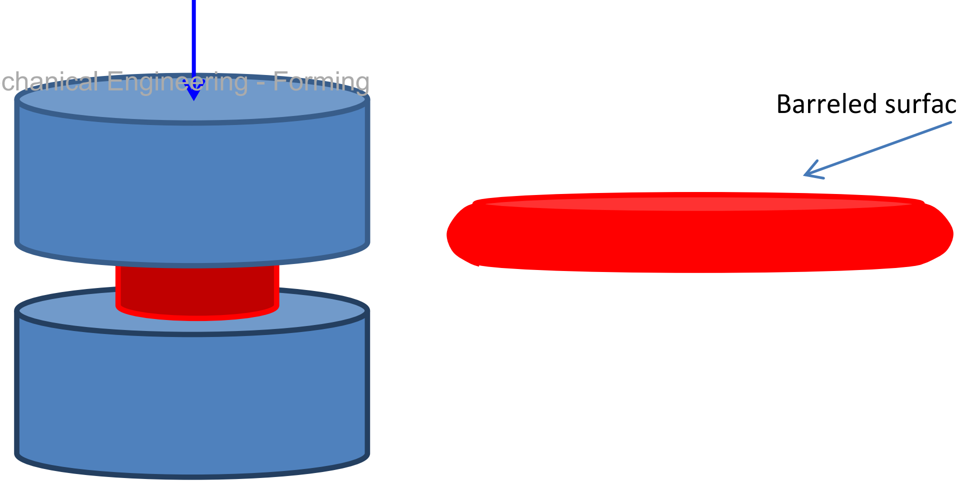
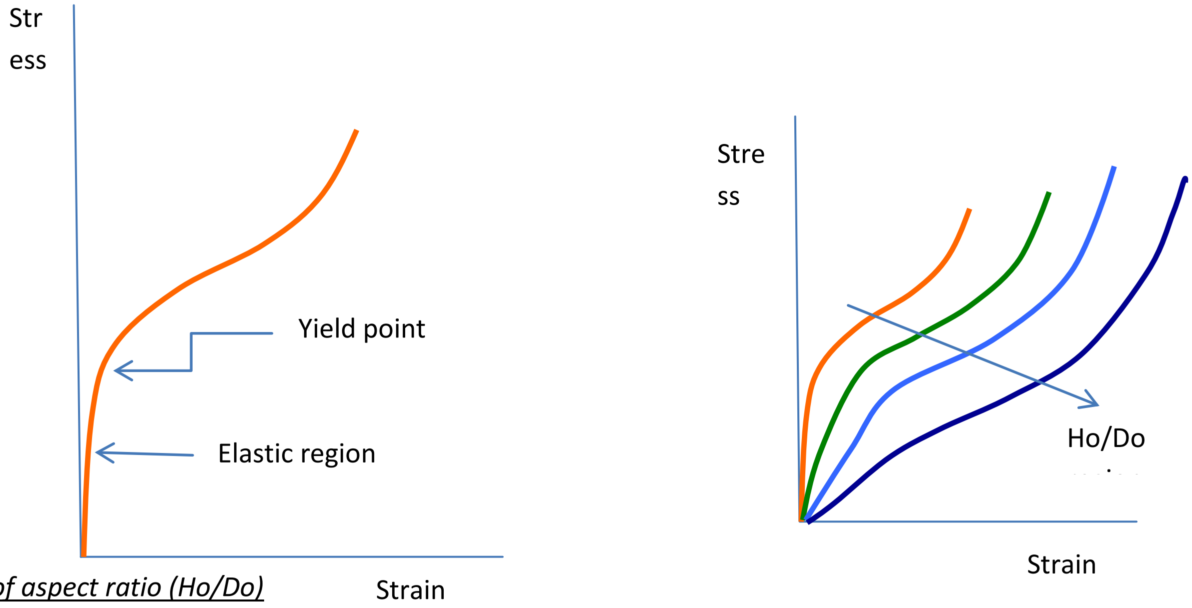


Fig. 4.1.1.1: Simple compression test and bulging of the billet due to non-uniform flow

Figures below show the stress-strain curve for specimen subjected to axial compressive stress



Effect of aspect ratio (Ho/Do)

Fig. 4.1.1.2: Stress-stress diagram for simple compression

Aspect ratio – the diameter of billet divided by its height can have greater effect on compressive behavior of the billet. As seen from figure above, if the billet has high aspect ratio, the compressive stress required for a certain strain is higher. This is due to the difficulty of material deformation as a result of shear zone and also due to larger area over which the force is getting applied.

4.1.2. Plane strain compression

Like simple compression test, the plane strain conpression test is another method of determination of flow stress. In this test, a thin sheet is subjected to compression using a pair of platens. The mode of material flow in this test is plane strain compression – there is no strain along width direction of the sheet.

The yield stress obtained from thie test is plane strain yield strain, Y' = [2/√3]Y

For ductile materials, true stress-true strain curves under compression and under tension can be considered identical.

In some forming operations like bending, the material is subjected to tensile stress and then to compression test. When a material is subjected to tensile loading upto yield and then compression, the yield strength of the metal in compression may be lower than that in tension. This phenomenon is called Bauschinger effect. The lowering of yield in compression [or in tension if prior compression is affected] is called strain softening. Usually in metal forming analysis, this effect is neglected.

w> 5h

w > 5b

b > 2h

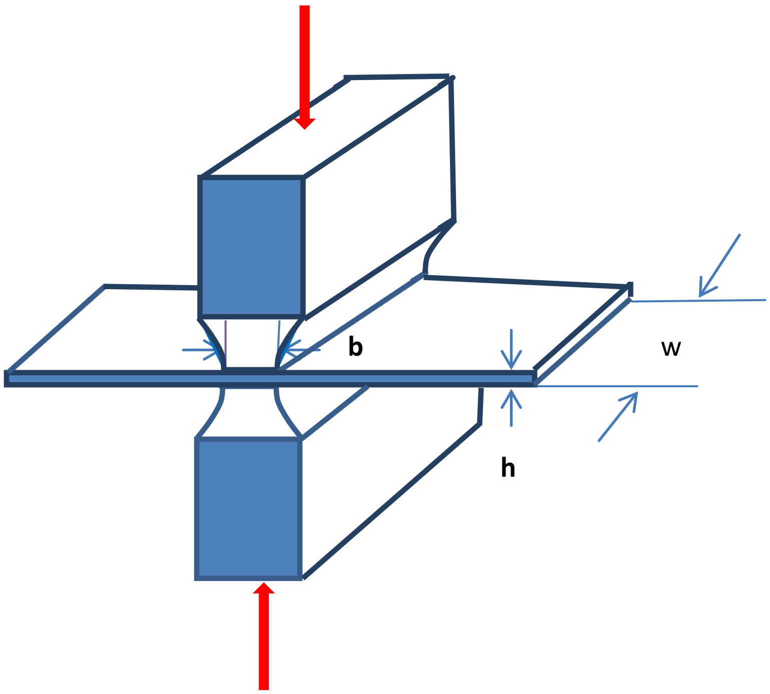


Fig. 4.1.2.1: Plane strain compression test for sheet metal

4.2Torsion and bending tests:

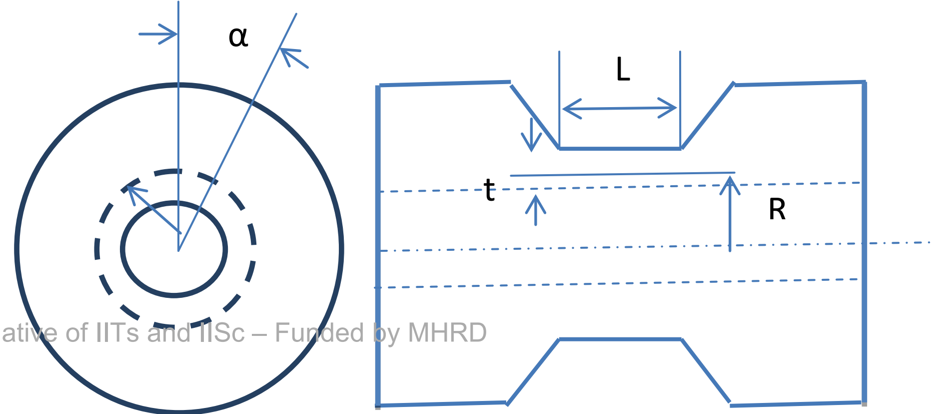


Fig. 4.2.1: Torsion test specimen

In torsion test, a hollow cylindrical specimen with a reduced crosssection midway is subjected to a torque T. The shear stress on the hollow section $\tau = T/2\pi R^2 t$, where R is radius of mean section at mid section of the tube, t is thickness of tube.

Shear strain $\gamma = R\alpha/L$ where α is angle of twist in radians and L is length of mid section.

In metal forming, the torsion test done at elevated temperatures serves as a very useful test for determination of flow stress (forgeability). Hot torsion test is very useful for determination of flow stress at high strain rates – strain rates upto 20 are involved in this test. Moreover, in hot torsion test, strain rate remains constant, as rpm remains constant, because thre is no change in area of cress-section, no necking.

Shear stress – shear strain curve from a torsion test is shown below:

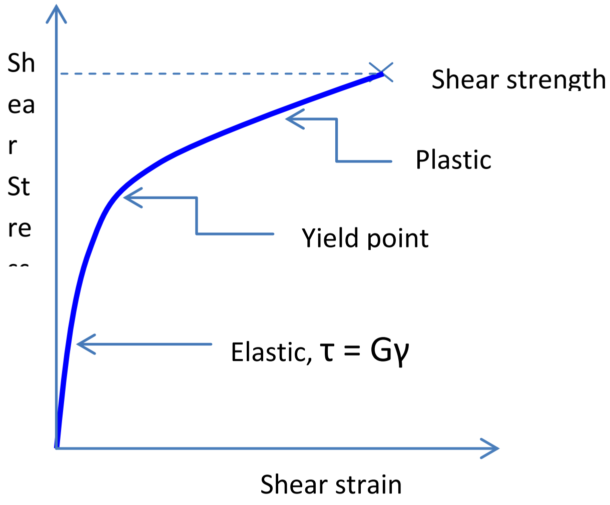


Fig. 4.2.2: Shear stress- shear strain curve

Elastic shear stress and shear strain are related by: $\tau = \gamma G$, where G is shear modulus.

Shear modulus is related to elastic modulus by the relation:

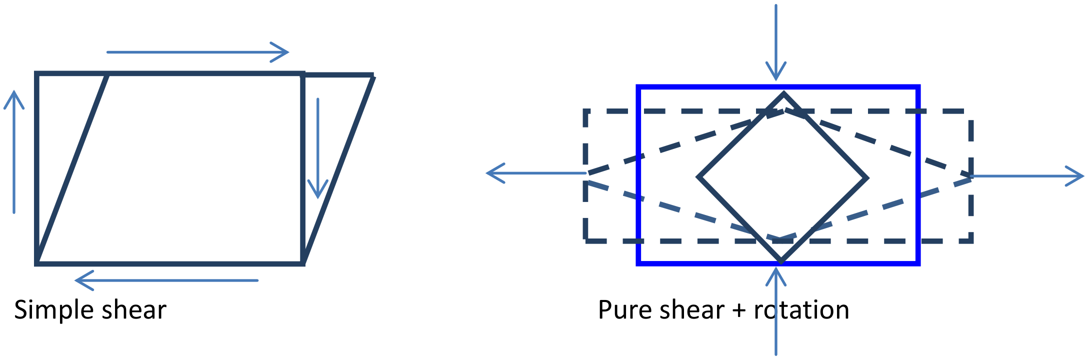
$$G = \frac{E}{2(1+\gamma)}$$

At fracture, the shear strength of the material is taken to be ¾ of tensile strength.

In shear test, the crosssection of the specimen does not change, therefore necking problem does not arise.

Shear deformation in materials can happen in two ways, one is simple shear and the other is pure shear.

Simple shear can be thought as combination of pure shear and rotation


Simple shear

Pure shear + rotation

Fig. 4.2.3: Shear Deformation

4.3 Bending test:

Ceramic materials are tested for their modulus of rupture or rupture strength by bend test. Ceramics are difficult to prepare for tensile or shear tests, as they are brittle and difficult to hold. In bend test, a rectangular cross section specimen is simply supported at ends and load is applied at one point (Three point bending) or two points on top (Four point bending).

The stress at which the specimen fractures due to bending is called transverse rupture strength. It is given as $\sigma = Mc/I$, where M is bending moment, c is half of specimen thickness and I is moment of inertia.

The transfer rupture strength TRS is given as:

$TRS = 1.5\ FL/bt^2$, where F is force at rupture, L is length between supports, t is thickness of specimen, b is width of specimen.

4.4 Hardness test:

Hardness is defined as the resistance to plastic indentation, surface scratchor wear.

Hardness test is a simple but important test for assessing the mechanical properties of materials. Hardness is a very useful surface characteristic because it helps in assessing the surface quality against wear and tear. For tools and dies, hardness is considered as important as it can be measured easily and it gives significant assessment of surface resistance to wear.

It is sometimes used for correlating with tensile strength.

There are a number of ways by which hardness is determined. In general, in all these tests a hard indenter is used for making indentation on surface.

From indentation geometry, hardness values are obtained.

The indentation geometry depends on geometry of indenter as well as the force applied during indentation. Different materials may require different amounts of forces to be applied for making indentations on surface.

In Rockwell hardness test, the difference in depth of penetration produced between major and minor indentations is taken as hardness value. Depending on the range of hardness values obtained, different hardness scales are used. For example, 55HRC refers to a hardness value of 55 as measured in Rockwell hardness C scale.

In Brinell test, a steel or tungsten carbide ball 10 mm in diameter is pressed with different loads, 500, 1500, 3000kg. From the measurement of the dia of the indentation the hardness is calculated using the formula:

$HB = \frac{2P}{(\pi D)(D-\sqrt{D^2-d^2})}$ where D is diameter of indenter, d is diameter of indentation, P is load.

The impression made on surface depends on the load used.

Vicker's hardness test uses a diamond pyramid indenter with loads from 1 kg to 120 kg.

Indentations produced in this test are less than 0.5 mm in diameter.

However, the hardness values are independent of load.

Vicker's test can be applied for wide range of materials.

$HV = 1.854P/L^2$

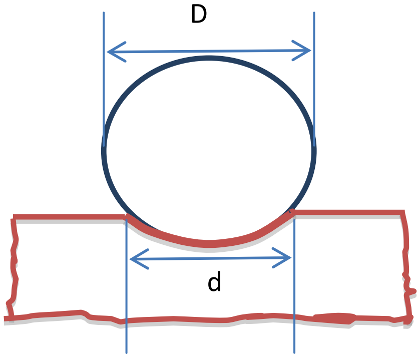


Fig. 4.4.1: Indentation in Brinell test

Knoop hardness test also called microhardness test uses an elongated

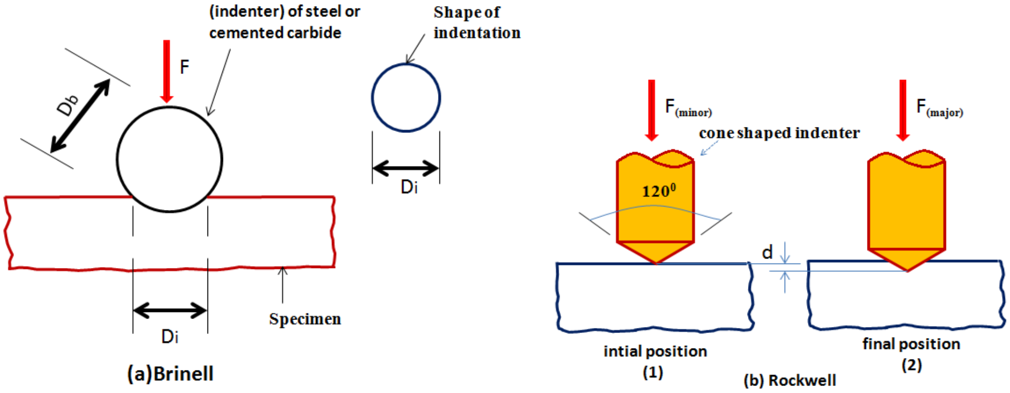
diamond indenter of size mm to 0.1 mm with loads ranging from 2.5 to 5 kg.

$KH = 14.2P/L^2$. Indentations produced are very small. This test can be used for finding hardness of individual grains.

Hardness can be related to yield strength for some materials in linear form: H = C Y

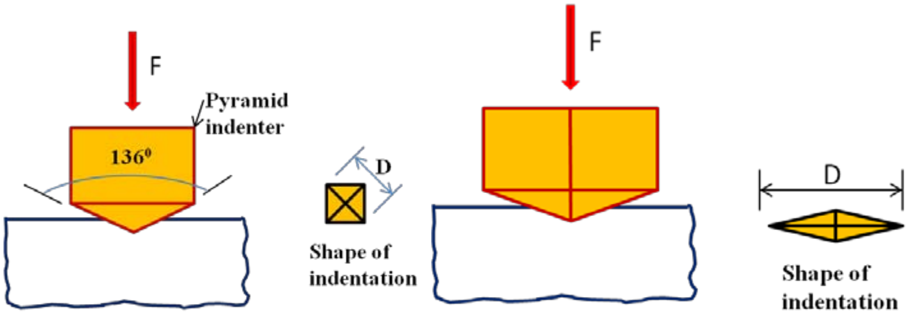
Where C is a constant and Y is yield strength. Similarly, the Brinell hardness and ultimate strength are related as: UTS = 3.5 BHN.

Hardness can be conducted at elevated temperatures [hot hardness], using suitable furnace enclosure. Hot hardness is important for tool and die materials. For materials hot hardness decreases with increasing temperature. Ceramics have good hot hardness and high compressive strength.



(a)Brinell

(b) Rockwell



(c) vikers

(d) Knoop

Fig. 4.4.2: Indentation and indenters in various hardness tests

Table 4.4.1: Hardness values of some alloys

Material	Rockwell hardness	Brinell hardness	Knoop hardness/Vicker’s hardness
Gray cast iron		10 HRC	
Aluminium, cold worked	30 HB		
Low C steel hot rolled	200 HB	95 HRB, 15 HRC	
Austenitic stainless steel	150 HB	85 HRB	
Heat treated alloy steel	300	33 HRC	
Nylon	12 HRB		
PVC	10 HRB		
Tool steel			850 HK/800 HV
Alumina			1500 HK/2200 HV
Tungsten carbide			1900 HK/2600 HV

4.5 Impact tests:

Impact toughness refers to energy absorbed by a material during impact loading.

Impact toughness or impact strength is determined by Charpy or Izod impact test. A notched specimen supported at one end or both ends is broken using a swinging pendulum. The energy dissipated during fracture if the specimen is the impact toughness.

In Charpy test, the notched specimen of square cross-section is supported on both ends and held horizontal. In Izod test, the notched bar is held vertical, supported on one end.

Materials with high ductility have high impact toughness. Toughness is important in ductile to brittle transition of materials.

4.6 Residual stress in metal forming:

Residual stresses are the locked-in stresses which are left inside the material after working.

Residual stresses are caused due to inhomogeneous deformation in material during forming process.

Cold worked materials have greater residual stress due to locking up of dislocations.

Phase changes can also cause residual stresses. For example martensitic transformation in steel involves volume changes at microscopic levels, this induces residual stress. Temperature gradients also can cause residual stress due to restraint on material expansion during heating or contraction during cooling phase.

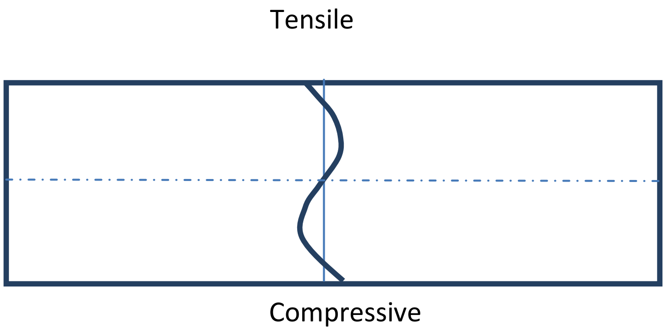


Fig. 4.6.1: Residual stress in bending

In bending there is non-uniform deformation. Outer fibers of the material are subjected to tensile stresses while section inside the neutral axis are subjected to compressive stress. Upon release of external load, residual stress remains in the material due to difference in elastic and plastic deformation within the section of the material.

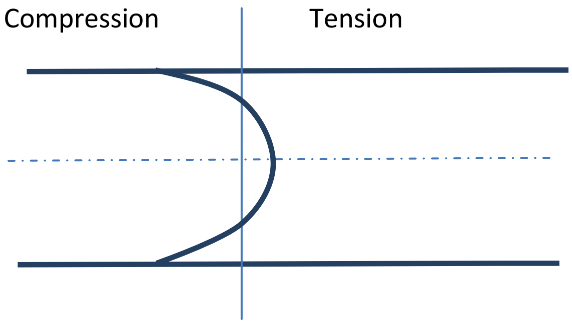


Fig. 4.6.2: Residual stress in rolling

Residual stress introduces distortion, dimensional changes after forming or machining operation. Stress relaxation may also cause dimensional and shape changes in finished products.

Material behavior in metal forming

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5.1 Flow stress:

Flow stress is the stress required to sustain a certain plastic strain on the material. Flow stress can be determined form simple uniaxial tensile test, homogeneous compression test, plane strain compression test or torsion test.In forming of materials, we are concerned with flow stress of material being formed, as this affects the ability of material to undergo deformation. Factors such as strain rate, temperature, affect the flow stress of materials. A simple power law expression for flow stress of a material which does not show anisotropy can be expressed as:

$\sigma = k\varepsilon^n$where n is known as strain hardening exponent.

Higher strain hardening exponent values enhance the flow stress. Similarly, flow stress is enhanced with increase in strain rate during a plastic deformation process.

Effect of strain rate on flow stress becomes more pronounced at higher temperatures. AT higher temperatures [hot working], strain hardening may not have effect on flow stress. However, during cold working effect of strain on flow stress cannot be neglected. In such cases, average flow stress can be determined between two given strains.

In hot forming, temperatures of working are above recrystallization temperature. Therefore, the grains of the metal get elongated along direction normal to applied force, giving raise to anisotropy. During recovery process, locked up dislocations get released. Residual stresses are reduced. Recrystallisation of new grains can happen when the metal gets heated above recrystallization temperature. Secondary grain growth may follow primary recrystallization. In hot working, metal may get softened after hot deformation process. Recrystallised grain size affects the flow stress of material.

A general expression for flow stress, encompassing temperature, strain, strain rate, recrystallisation has been given in the form:

$$\sigma = \frac{2}{\sqrt{3}(1-m)} K\varepsilon^n \dot{\varepsilon}^m \exp\left(-\beta T\right)$$

n is strain hardening exponent, m is strain rate sensitivity exponent, T is temperature.

Materials are subjected to complex states of stresses during forming. Stress required for forming, yield or flow stress therefore depends on several factors, such as strain, strain rate, temperature etc.

From the uniaxial tensile test, one can understand material behavior considerably. Form the tensile test data, we can determine flow stress, though this method has limitations due to localized deformation called necking.

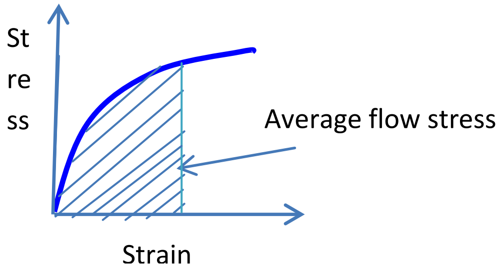
Flow curve is the stress-strain curve for a material in the plastic range. It describes material behavior in metal forming. From flow curve, we can determine the flow stress as

$$\sigma = k\varepsilon^n$$

In forming processes, such as forging, the instantaneous flow stress can be found from the flow curve, as the stress required to cause a given strain or deformation.

In extrusion, for example, the flow stress considerably changes during the forming process as the material gets work hardened considerably. In such cases, an average flow stress is determined from the flow curve. The average flow stress is given as:

$\sigma_{av} = \frac{K\varepsilon^n}{1+n}$where ε is maximum strain during deformation process and n is strain hardening exponent.



Knowing the final strain in the forming process, one can calculate flow stress using above equation.

5.2 Work done in deformation processing:

The plastic strain energy during deformation of a material is defined as energy stored in the material when it gets plastically deformed. The work done during the deformation is stored as strain energy. For plastic deformation under uniaxial deformation, it is given by the expression:

dW = Force X change in length of the specimen = Stress X Initial Area X Strain X Initial length

This can be written as:

dW/Volume = stress X strain increment

Strain energy per unit volume = stress X strain increment

$$du = \sigma d\varepsilon$$

This upon integration between zero strain and a finite plastic strain ε, gives:

$$u = \frac{K\varepsilon^{n+1}}{1+n} = \sigma_{av}\varepsilon$$

For triaxial stress, the plastic work per unit volume is given as:

$$du = \sigma_1 d\varepsilon_1 + \sigma_2 d\varepsilon_2 + \sigma_3 d\varepsilon_3$$

This energy represents the minimum energy required for deformation without friction, redundant deformation etc.

In reality, deformations happen with friction at workpiece-tool interface. Further, there is in- homogeneous deformation due to friction. Such inhomogeneous deformation leads to additional shear deformation. This is called redundant deformation because shearing is not a part of the desirable shape change of the material. Work is involved in shearing material. This work is known as redundant work.

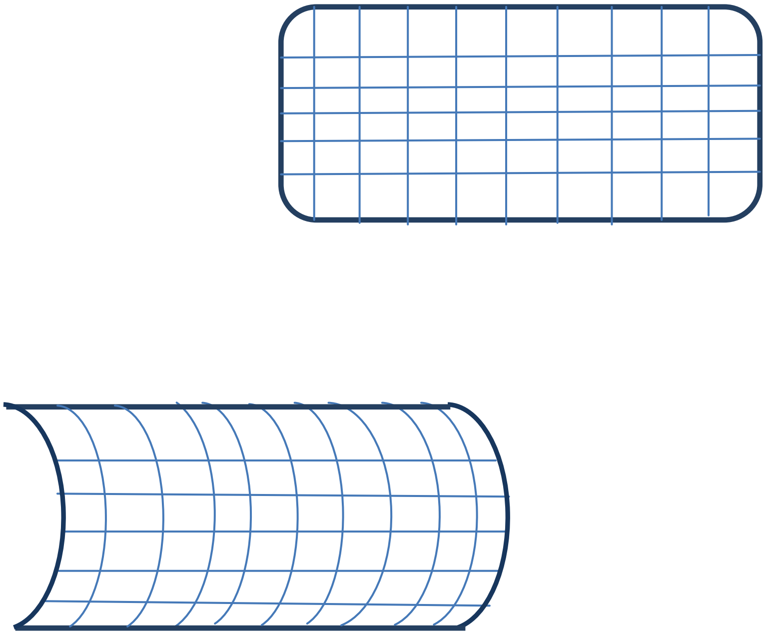


Fig. 5.2.1: Redundant shear deformation in forging process

5.3 Deformation zone geometry:

Bulk deformation of materials happen generally within converging die shapes. The small region of the die through which the metal is subjected to plastic deformation is called deformation zone.

Geometry or shape of the deformation zone affects the redundant deformation work, and hence the total forming force.

Deformation zone geometry also affects the residual stress, internal defects during forming.

Deformation zone geometry is defined by the parameter Δ. This parameter is defined as ratio of thickness or height of deformation zone to contact length of deformation zone.

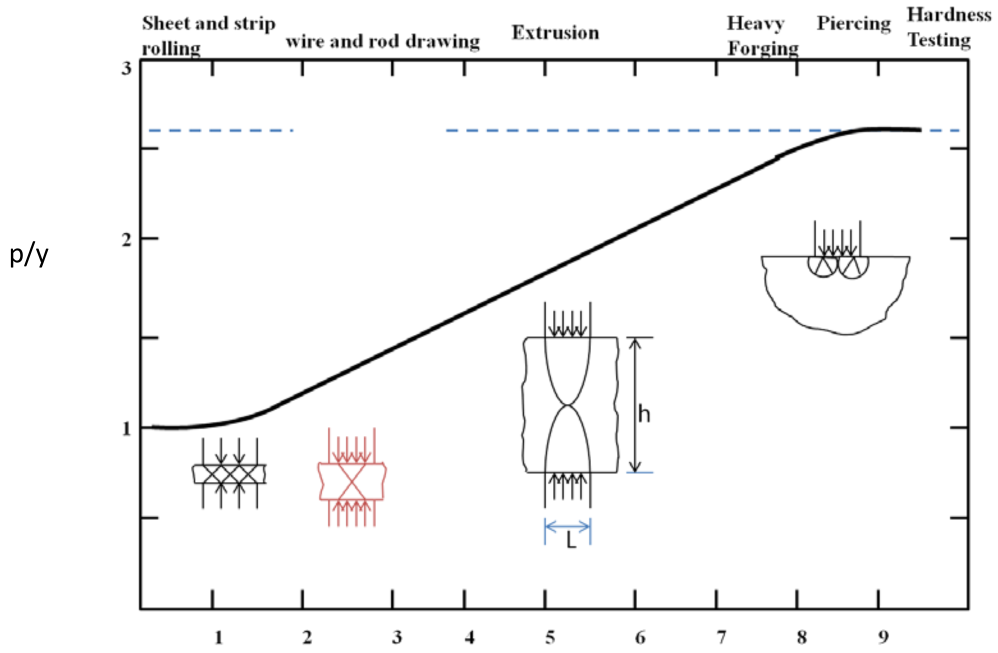
$$\Delta = h / L$$

For extrusion it can be shown that $h = (h_o + h_f)/2$ and $L = (h_o - h_f)/2\sin\alpha$. This factor increases with increasing die angle and decreases with reduction.

Redundant strain is expressed by a parameter ϕ, which is a function of Δ.

$\phi = 1 + \Delta/4$ for plane strain deformation

As deformation zone geometry increases, redundant strain increases. This leads to increase in redundant work.



Δ

Fig. 5.3.1: Effect of deformation zone geometry parameter on various forming processes

As observed from the above diagram, the deformation pressure increases with increase in deformation zone geometry, due to increase in redundant work. Also smaller h/L value, lower is forming pressure – in the absence of friction. However, effect of friction increases in smaller h/L cases. High Δ leads to high residual stress in the formed part.

Friction in forming is considered in the next section.

The total energy required during forming can be now written as:

$u_{total} = u_{ideal} + u_{friction} + u_{redundant}$

Forming efficiency is now defined as $\eta = u_{ideal} / u_{total}$

Rolling process has a high efficiency of 75 to 95% due to its low redundant deformation and smaller deformation zone geometry. Whereas, processes with high deformation zone geometry, such as forging and extrusion have low efficiency, 30 to 65%.

5.4 Friction in metal forming:

Surface asperities on two surfaces in contact get interlocked with each other. When a surface tends to slide against another stationary surface, say a die surface, there is a shear stress induced at interface which opposes the flow of material. This condition is called sliding friction.

Condition of sliding friction or sticking friction can arise at the interface between the workpiece and die/tool in forming operations.

Sliding friction arises due to surface shear stress opposing the metal flow. Friction is undesirable as it increases the deformation work required, leads to non-homogeneous deformation of material, causes tool wear, causes residual stress in the product and may lead to cracking of surface.

Coefficients of friction in forming processes are quiet high. If coefficient of friction becomes very high it leads to a situation called sticking friction. In this case, the surface shear stress exceeds shear yield strength of material, the two surfaces adhere to each other. Metal beneath the surface undergoes shear deformation.

Theoretical forming pressure without friction is: $p = \sigma_f$[flow stress].

With sliding friction, having coefficient of Coulomb friction $\mu = \tau/p$, the forming pressure increases exponentially along the interface, as given below for a disc under forging:

$P = \sigma_f(\exp^{2\mu/h(a-r)})$, where h is height of billet, a is radius of the cylindrical billet. As a result of friction, forming pressure rises exponentially, forming a friction hill in the lateral direction.

Friction factor m is sometimes used in place of coefficient of friction.

$m = \tau / k$, where k is shear yield strength.

m is independent of normal pressure at interface and it is easy to measure.

Use of Coulomb coefficient of friction is sometimes misleading, as we find from the definition of coefficient of friction that μ decreases with increasing pressure, which is not correct.

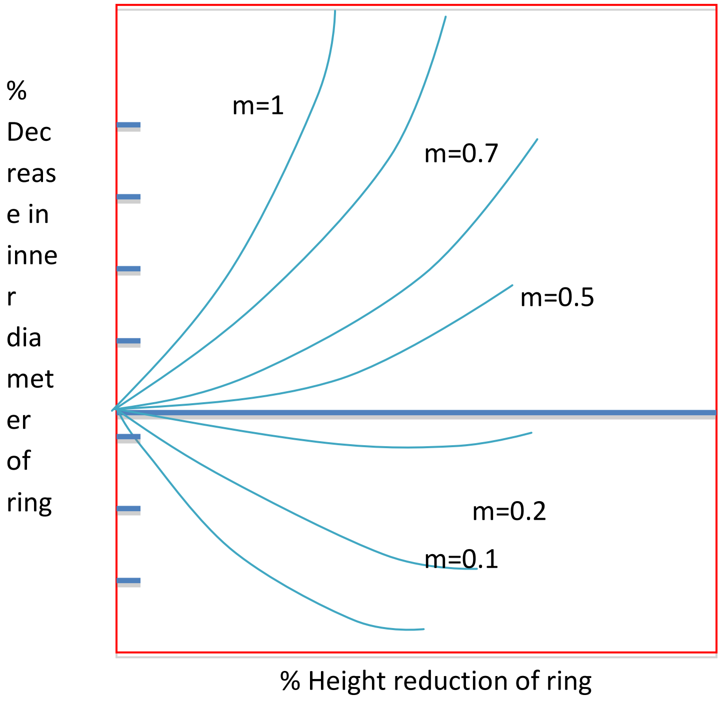
Therefore, m is preferred in analysis of friction– especially in hotworking.

Lubrication is necessary in order to reduce friction in metal forming.

For cold forming operations, fats, fatty acids, mineral oils, soap emulsions are generally used. For hot forming, glass, graphite, mineral oils can be used as lubricants.

The coefficient of friction μ or friction factor m can be measured using the ring compression test. In this test, a ring of OD:ID:Height = 6:3:1 is subjected to axial compression. With incremental load applied, the change in inner dia of the ring is taken to be a measure of friction factor. If there is no friction, the inner diameter of the ring increases. With friction, there Is decrease in inner diameter of the ring. The test can be repeated for different types of lubricants – under varying μ.

With the calibration curves drawn between change in inner dia and height reduction, one can find out the friction factor for given condition of interfacial friction. There is no need to measure the deformation force in the test.



5.4.1:Calibration curves for ring compressiontest

5.5 Effect of temperature in metal forming:

Forming process requires stress above flow stress of the material being deformed. The effect of external work done on work piece during forming is converted into heat. About 5 to 10% of the work is stored within as internal energy. Friction can also result in heating and increase in internal energy of workpiece.

Assuming frictionless deformation, the temperature increase during metal forming operation can be written as:

$\Delta T = u_{plastic} / \rho C_p$, where $u_{plastic}$ is plastic work done per unit volume of work piece. C_p is specific heat and ρ is density.

With friction,

$\Delta T = \lambda u_{total} / \rho Cp$, where λ is fraction of deformation work converted to heat. Normally, $\lambda = 0.95$ to 0.98.

Temperature rise is calculated using stress-strain curve, as the plastic work is calculated as the area under stress-strain curve for plastic flow.

For slow deformations, the temperature rise of the work piece may be small as the heat generated gets dissipated through the die, surrounding air, etc. However, adiabatic condition may prevail under large deformation speeds, resulting in large rise in temperature of the work piece. This may cause incipient melting. Therefore, strain rate also influences the temperature rise during working.

For low carbon steel, the temperature rise for a true strain of 1 has been estimated to be 553 K. This is without heat lost from the billet.

5.5.1 Cold and hot forming:

Cold forming is carriedout at a temperature lower than recrystallization temperature of the work piece material. Hot working is a process carried out at temperatures above recrystallization temperature, namely, 0.6 T_m. High strain rates – 0.5 to 500 s^{-1} are involved in hot working. No strain hardening takes place in hot working. Processes of recrystallization, recovery and grain growth dominate in hot working. Energy required for hot working is low, as flow stress decreases with increase in temperature. Large strains (ε = 2 to 4) are possible in hot forming because of recovery process. Due to oxidation on surface during hot working, poor surface finish and poor dimensional tolerences are inherent defects. Die wall chilling may result in non-uniform material flow.

Upper limit for hot working is hot shortness, in which the metal becomes brittle above a certain temperature due to grain boundary melting or melting of low melting phase such as sulfur in steel.

Metals with high thermal conductivity will require higher working temperatures or rapid working.

During hot working, material softening happens due to two mechanisms – dynamic recovery or dynamic recrystallization. In dynamic recovery, dislocation cross-slipping, climbing occurs. This mechanism is predominant in high stacking fault energy metals, with low activation energy for creep. On the other hand for metals with low stacking fault energy, like copper, nickel, the dynamic recrystallization is predominant mechanism of softening. During hot working static recovery can happen in between the working phases, thereby softening the metal. Rapid cooling after hot working may bypass this static recovery, thereby retaining the high strength of the metal. Strain induced precipitation or phase transformation can increase the flow stress, reduce ductility. Age hardenable (Al) alloys are subjected to freezing temperatures before forming, to suppress precipitation during forming. Thermo mechanical treatments can be used for achieving optimum levels of strength and hardness.

Cold working leads to work hardening. The formed material may have to be annealed to relieve internal stresses and reduce hardness and strength after cold forming. However, if high strength and hardness are desirable, normally cold worked structure is retained. Cold working has high dimensional accuracy.

Working on a metal at temperatures above room temperature but below recrystallization temperature is called warm working. Warm working may have the advantages of reduced working pressures, reduced levels of residual stresses and oxidation, improved surface finish and dimensional accuracy.

5.6 Workability:

Materials differ in their ability to undergo plastic deformation. The extent of plastic deformation in a material is dependent on the materials grain structure, nature of bonding, presence of defects like dislocation and external factors such as temperature. Workability is the ease with which a material can be subjected to plastic deformation to achieve the desired shape without crack formation. In case of ductile materials the limit of forming is dictated by the beginning of necking. Once necking starts, due to localized deformation, further deformation of the work piece to finished shape becomes impossible. Therefore, in most of materials, the starting of necking is considered as the limit of working or forming. Workability is dependent on material characteristics and external factors such as tool and die geometry, friction, strain rate etc.

The other criterion for workability may be the formation of cracks on the surface or within the material during the forming process. Cracks on external surface may form due to excessive tensile loads or friction. Internal cracks may form due to the presence of voids, second phase particles etc. Necking during tensile deformation may result in formation of voids, which may grow in size during loading. Cracks result due to excessive growth of voids and their coalescence. In compressive loading, generally surface cracks are formed due to excessive tensile stresses induced on the bulged surfaces. Bulging is a non-uniform deformation during compressive loading of billets.

A generalized fracture criterion may serve as a way of establishing workability of ductile materials. Combinations of stress and strain in ductile materials can lead to fracture unless the tensile stress induced reaches a critical value. More easily, tensile and compressive strains are correlated with each other in order to arrive at a criterion for workability. The simple upset test serves as effective technique for developing the workability limits for materials. By varying the diameter to height ratio of cylindrical billets, which are subjected to simple upset test, one can develop fracture criteria.

The following graph is developed from simple upset test:

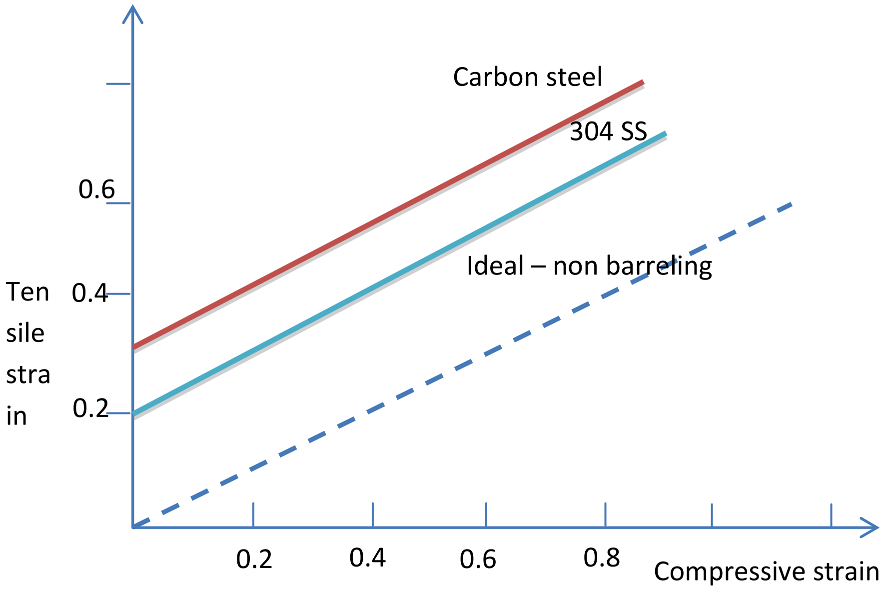
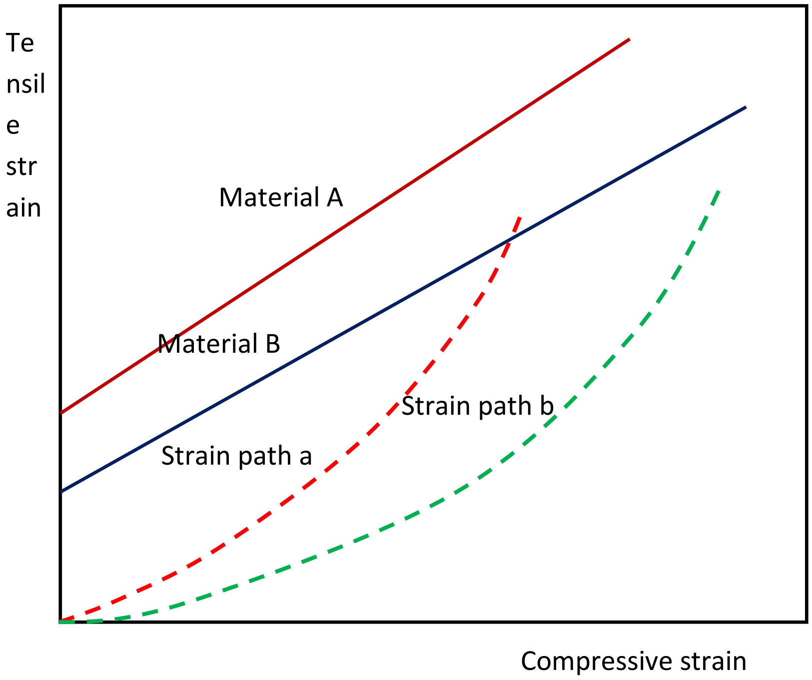


Fig. 5.6.1: Fracture limits for some materials

In the figure shown above, the broken line having a slope of ½ represents fracture limit for an ideal material subjected to upsetting without bulging. Any combination of tensile and compressive strains which lead to fracture is represented by a point located above this line. Similar fracture criteria lines for stainless steel and carbon steel are also shown. Any combination of strains represented by points below the limit line will not cause fracture. Note that the tensile strains at fracture are found out from bend test.

H.A.Khun developed a workability diagram which includes the process factor in addition to the strain limit factor (a material factor) for fracture.



5.6.2: Workability limit diagram developed by H.A.Khun for cold upsetting of a bolt head

The strain paths, represented in figure as dashed lines, are obtained by drawing grid lines on surface of a model which is subjected to upset test. The solid lines represent fracture limit. For material B with strain path a as chosen mode of deformation, fracture is sure to take place at the strain represented as the point of intersection between the fracture limit line and strain path line. If on the other hand the strain path b is chosen for either material, the fracture is not likely to occur within the working limits of the forming (upsetting).

Stress transformation and Mohr's circle for stresses

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1. Stress transformation and Mohr's circle for stresses:

1.1 General State of stress

Consider a certain body, subjected to external force. The force F is acting on the surface over an area dA of the surface. Then the stress is defined as the intensity with which the force is acting.

We can write the stress at a point as:

$\sigma = \lim_{dA \to 0} dF/dA$ = F/A if the stress is uniform

In general, the force acting is acting on a surface along some arbitrary direction can be resolved into components acting perpendicular to the given surface and also parallel to the given surface. Each component of force divided by the area over which it acts gives rise to three different states of stress on the surface, namely, one normal stress and two tangential stresses. These three stresses can be thought of acting along the three conventional x, y, z axes.

The state of stress on a 3dimensional object can be specified with 9 stress components. 3 normal stresses and 6 tangential (shear) stresses. This is diagrammed below:

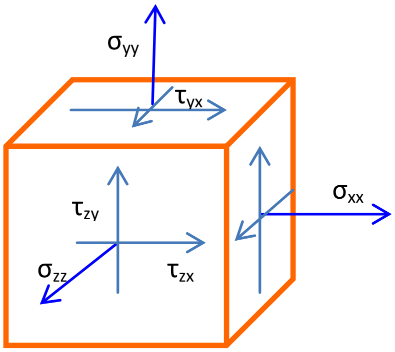

Fig. 1.1.1: Description of three dimensional state of stress

The 6 shear stress components, due to the requirement of zero rotation of the element or for moment balance, reduce to three shear stress components.

For satisfying moment balance, we have $\tau_{xy} = \tau_{yx}$and so on.

Normal stresses are represented with repeated subscripts, the first subscript represents the direction and the second subscript represents the plane on which it is acting. In case of shear stress, the first subscript represents the plane on which it is acting and the second subscript represents the direction along which the shear stress is acting.we can interchange the definition for the two subscripts of stress.

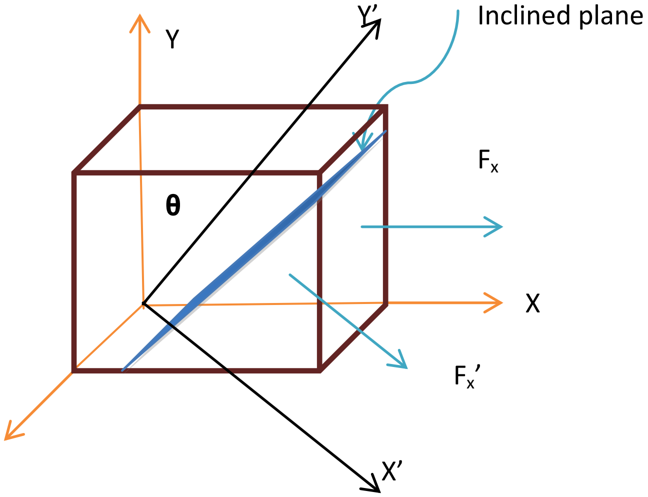

Fig.1.1.2: Stress on an inclined plane

Consider the force F_x acting on the right face of the cube, along x axis, as shown in diagram above. Consider a plane inclined with an area of A', as shown shaded. The normal to the shaded plane Y' is inclined at angle theta with Y axis.

F_x' the force acting along X' direction can be written as:

$F_x' = F_x\cos\boldsymbol{\theta}$

Now the stress along X' direction, normal to a plane inclined at angle **θ**with xy plane is

$$\sigma_x' = \frac{Fx'}{Ax'} = \frac{F_x}{Ax/cos\theta}cos\theta = \sigma_x cos^2\theta$$

Similarly, we can write the shear stress on the inclined plane as:

$$\tau_{xy}' = \tau_{xy} sin\theta cos\theta$$

In the same manner one can obtained the expression for the transformed stress σ_y' as:

$$\sigma_y' = \sigma_y cos\theta sin\theta$$

We note from the above expressions that the transformed stresses involve sine and cosine functions of the angle of rotation of the axes.

We can generalize the expressions for transformed stresses by writing:

$$\sigma_{ij} = \sum_{n=1}^{3} \sum_{m=1}^{n} l_{im} l_{jn} \sigma_{mn}$$

l_{im} is the direction cosine of angle between the axes I and m.

Triaxial state of stress may be rarely come across, in applications such as thick walled pressure vessels. In metal forming operations, triaxial state of stress is rarely come across. Therefore, matters get simplified with some assumptions. The first important assumption is plane stress condition.

1.2 Plane stress:

Many metal forming processes involve biaxial state of stress.

If one of the three normal and shear stresses acting on a body is zero, the condition of stress is called plane stress condition.All stresses act parellel to x and y axes.

i.e. $\sigma_{zz} = 0$, $\tau_{xz} = 0$

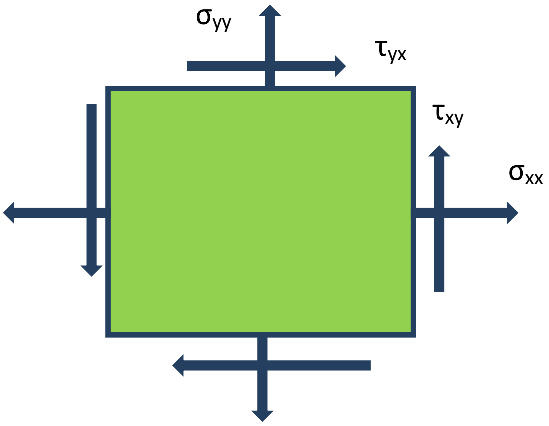

Fig. 1.2.1: Plane stress condition

Plane stress condition is come across in many engineering and forming applications.

When we consider crystalline solids, deformation is predominantly by slip of atomic planes of atoms along preferred directions.

Normally, slip can be easy if the shear stress acting on the slip planes is sufficiently high and acts along preferred slip direction. Slip planes may be inclined with respect to the external stress acting on solids. It becomes necessary to transform the stresses acting along the original axes into the inclined planes. Stress transformation becomes necessary in such cases.

1.3 Stress transformation in plane stress:

Consider the plane stress condition acting on a plane as shown. The stresses are to be transformed onto a plane which is inclined at an angle θ with respect to x, y axes.

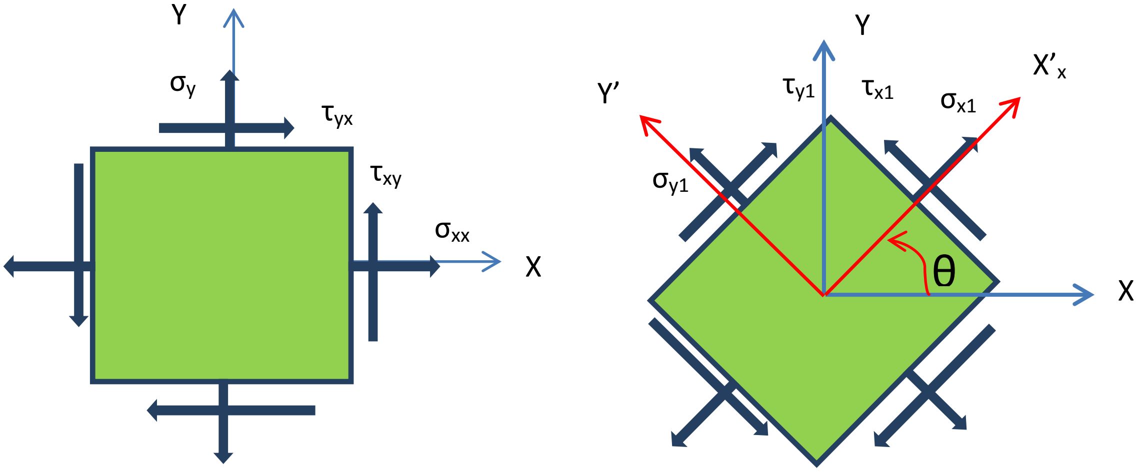

Fig. 1.3.1: Representation of stresses on inclined plane

Let X' and Y' be the new axes got by rotation of the x and y axes through the angle θ.

After the plane has been rotated about the z axis, the stresses acting on the plane along the new axes are to be obtained.

In order to obtain these transformed stresses, we take equilibrium of forces on the inclined plane both perpendicular to and parallel to the inclined plane. Or else, we can write the expression for transformed stress using the direction cosines:

$$\sigma_x' = l_{x'x}^2\sigma_x + l_{x'y}^2\sigma_y + 2l_{x'x}l_{x'y}\tau_{xy}$$

$$= 2cos^2\Theta\sigma_x + 2sin^2\Theta\sigma_y + 2cos\Theta sin\Theta\tau_{xy}$$

Similarly, we could write for the y' normal stress and shear stress.

The transformed stresses are given as:

$$\sigma_{x_1} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta$$

$$\sigma_{y1} = \frac{\sigma_x + \sigma_y}{2} - \frac{\sigma_x - \sigma_y}{2} cos2\theta - \tau_{xy}\, sin2\theta$$

And

$$\tau_{x_1 y_1} = \frac{\sigma_x - \sigma_y}{2}\sin 2\theta + \tau_{xy}\cos 2\theta$$

Where σ_{x1} is the normal stress acting on the inclined plane and τ_{x1y1} is the shear stress acting on the inclined plane.

The above three equations are known as transformation equations for plane stress.

One is interested in maximum and minimum normal and shear stresses acting on the inclined plane in order to design components against failure.

The maximum normal stress and shear stress can be found by differentiating the stress transformation equations with respect to θ and equate to zero.

The maximum and minimum stresses are called principal stresses and the plane on which they act are called principal planes.

Maximum normal stress:

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{(\frac{\sigma_x - \sigma_y}{2})^2 + \tau_{xy}{}^2}$$

Maximum shear stress:

$$\tau_{max} = \sqrt{(\frac{\sigma_x - \sigma_y}{2})^2 + \tau_{xy}{}^2}$$

Also we find that $\tau_{max} = \frac{\sigma_1 - \sigma_2}{2}$

On a plane on which the principal normal stress acts, the shear stress is zero. Similarly, on a plane on which the principal shear is acting, the normal stresses are zero.

The angle corresponding to the principal planes can be obtained from:

$\tan 2\Theta = \frac{\tau_{xy}}{\frac{\sigma_x - \sigma_y}{2}}$for the principal normal planes

And $\tan 2\Theta = -\frac{\tau_{xy}}{\frac{\sigma_x - \sigma_y}{2}}$for principal shear plane

From this we find that the plane of maximum shear is oriented at an angle of 45° with respect to the planes of maximum or minimum normal stresses.

1.4 Mohr's circle for plane stress:

Stress transformation equations can be represented in the form: $(x-h)^2 + Y^2 = R^2$ which represents the equation of a circle. h is the distance of center, R is radius of circle.

For plane stress condition, the equation for Mohr's circle is gives as:

$$(\sigma_{x1} - \frac{\sigma_x+\sigma_y}{2})^2 + \tau_{x1y1}{}^2 = (\frac{\sigma_x - \sigma_y}{2})^2 + \tau^2{}_{xy}$$

Here center of circle is located at a distance of $\sigma_{av} = (\sigma_x + \sigma_y)/2$from origin.

Transformed equations of stress are represented graphically by a circle called Mohr's circle. It can be used for determining graphically the transformed stresses on a new inclined plane.

Positive x-axis is chosen as normal stress axis. Negative y axis is chosen as positive shear axis.

Suppose the state of stress, both normal and shear (σ_x and τ_{xy}) on the two faces of a cube is known.

Centre of the circle is located at the average stress along the x axis. Then the known state of stress is represented by a point with σ_x and τ_{xy} as coordinates.Another point diametrically opposite to this point is located with the coordinates corresponding to the stresses acting on the face which is at 90 degree to the first face of the cube.

Now a circle is drawn with distance between both pints as diameter.

Stresses on an inclined plane can be represented on the circle if the angle of inclination is known. Twice the real angle of inclination is represented on the Mohr's circle.

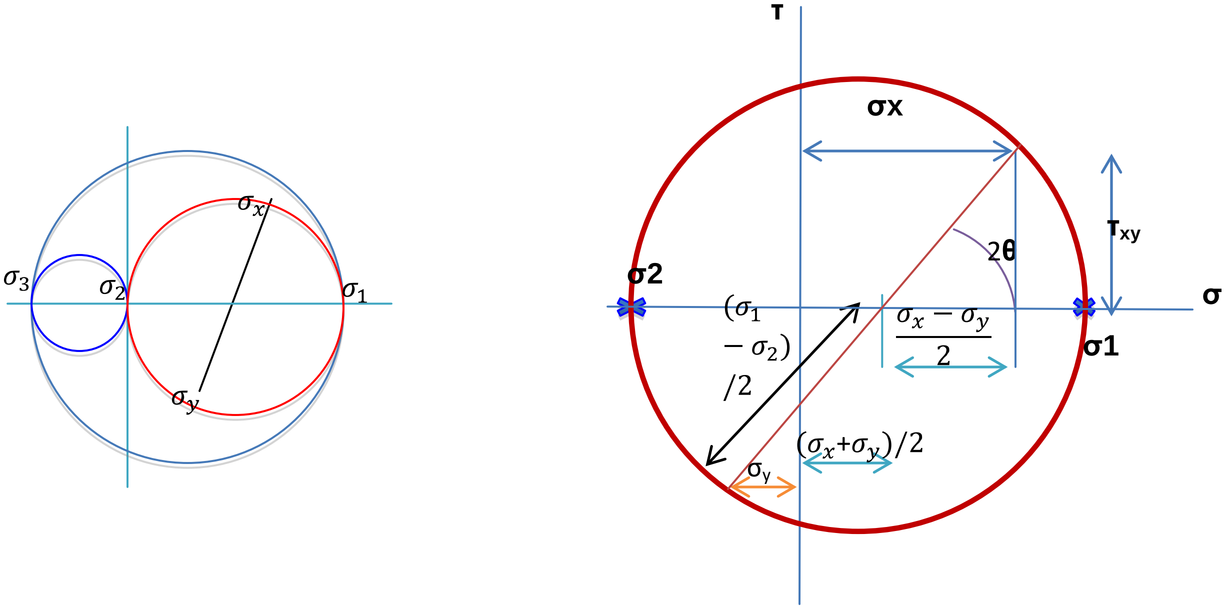

Fig. 1.4.1: Mohr's circle for triaxial and plane stresses

Strain Transformation equations

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1. Strain Transformation equations:

1.1 General state of strain

When a body is subjected to stress, it undergoes deformation. When deformation happens, the points in the body are subjected to displacement. Such displacements include deformation, translation and rotation. Normal stress causes deformation. Shear stress can cause both rotation and translation. While considering normal strain, we ignore rotation and translation.

Deformations in solids may also be due to volume changes or distortion, which is shape change. Displacements in rigid bodies are a linear function of distance.

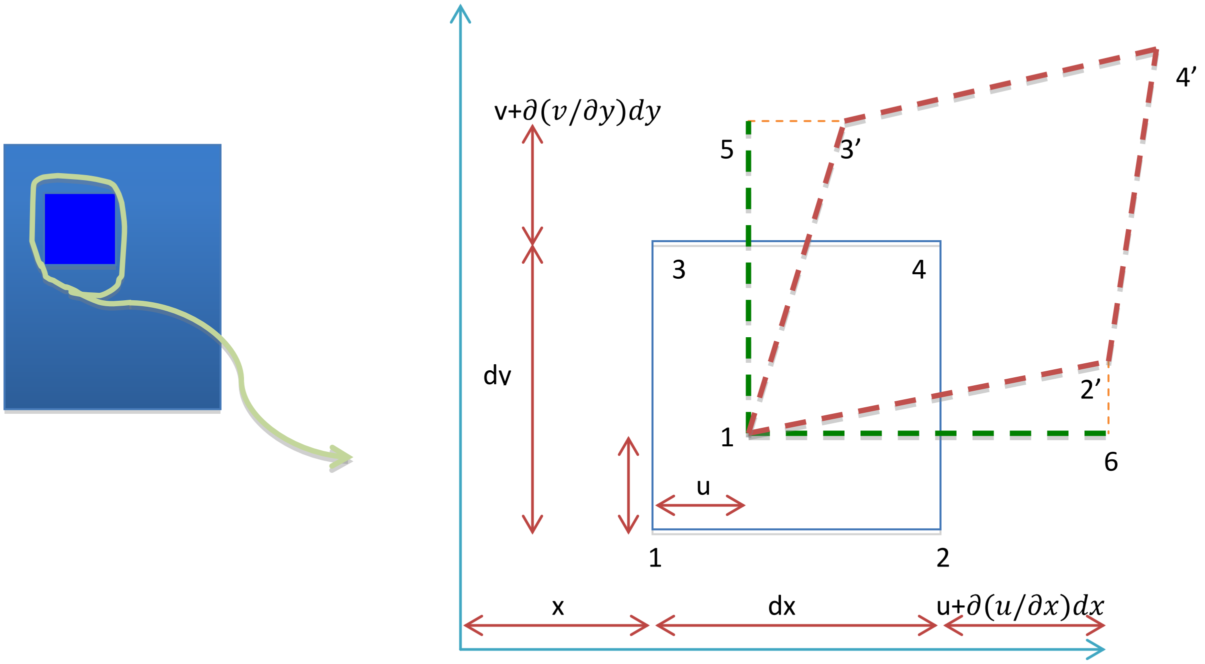

Fig.2.1.1: State of strains on a body – normal and shear

Consider a small elemental plane of a solid subjected to elastic deformation, as shown above. The sides of the element undergo distortion as shown by dotted lines. The side 1-2 gets translated and sheared to 1'-2', Let us ignore the rotation of the elements. The displacements of various points in the element is assumed to be linearly proportional to their distance. Farther points in the element will undergo more displacement. This assumption is valid for small displacements and elastic bodies.

Point 1 has a displacement of u along x axis and v along y axis.

Neglecting rotation, the side 1-2 has a linear strain $= \partial u/\partial x$.

Because, Strain on 1-2 = [(1-6) – (1-2)]/1-2

Similarly the side 1-5 has a strain $= \partial v/\partial y$

Now consider the angular strain (shear strain) on 1-6 and 1-5

Shear strain on 1-6 = $\partial v/\partial x$

Similarly, shear strain on 1-5 = $\partial u/\partial y$

Total shear strain = $\gamma_{xy} = (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})$

Now consider the rotation of 1-6 and 1-5:

We can write the total rotation = $\omega_{xy} = 1/2(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x})$

Here we consider anticlockwise rotation as positive

We are interested in transforming the strains along the given axes onto new axes which are inclined with the original axes at an angle. This may be similar to a situation in which we rotate the object itself through an angle and want to obtain the strains on the rotated object. The state of strains on an object subjected to stress can be represented with normal and shear strains. Only small strains can be transformed because for large strains, large angle changes may be involved.

While considering strain transformations, we consider a particular case, namely plane strain.

Plane strain condition is one in which the normal and shear strains along one of the three axes are zero.

$\varepsilon_z = 0$, $\gamma_{xz} = 0$, $\gamma_{yz} = 0$

The stress transformation equations derived for plane stress condition can also be applied for a condition of stress in which σ_z is also present. This is because σ_z is absent in the equilibrium equations.

This means that we can use the same transformation equations derived for stress for plane strain condition as well.

Normal strain is given as $\varepsilon_{xx} = \frac{\partial u}{\partial x}$,$\varepsilon_{xy} = \frac{1}{2}(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})$.

Shear displacement is split into strain and rotation. Shear involves both displacement and rotation.

Shear strain is given as:

$\gamma_{xy} = (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})$This strain is called engineering shear strain.

1.2 Strain transformations:

Let us assume plane strain condition.

We can write the strain transformations similar to stress transformations using direction cosines.

$$\varepsilon_x' = l_{x'x}^2\varepsilon_x + l_{x'y}^2\varepsilon_y + l_{x'x}l_{x'y}\gamma_{xy}$$

Similarly,

$$\gamma_{x'y'} = 2\varepsilon_x l_{x'x}l_{y'x} + 2\varepsilon_y l_{x'y}l_{y'y} + \gamma_{xy}\,(l_{x'x}l_{y'x} + l_{y'x}l_{x'y})$$

Here, $l_{x'x} = cos\theta \; and \; l_{x'y} = sin\theta$

Strain transformation equations for plane strain condition can be written as:

$$\varepsilon_{x_1} = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos 2\theta + \frac{\gamma_{xy}}{2}\sin 2\theta$$

$$\frac{\gamma_{x_1y_1}}{2} = \frac{\varepsilon_x - \varepsilon_y}{2}\sin 2\theta + \frac{\gamma_{xy}}{2}\cos 2\theta$$

The principal normal strains are given as:

$$\varepsilon_{1.2} = \frac{\varepsilon_x + \varepsilon_y}{2} \pm \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2}$$

Principal shear strain is:

$$\frac{\gamma_{\max}}{2} = \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2}$$

Minimum shear strain is of same magnitude as above but negative.

The similarity between plane stress transformation equations and plane strain transformation equations can be noted.

AT a point in a body, the principal stress and principal strain have the same direction.

1.3 Mohr's circle for strain:

Mohr's circle for strain is similar to that for stress. It is given below:

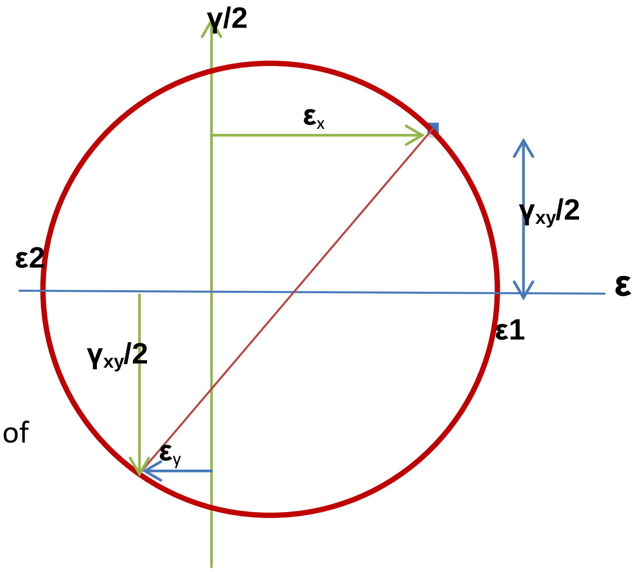

Fig. 2.3.1: Mohr's circle for plane strain

Note: The principal normal and principal shear stresses as well as strains are oriented at an angle of 45^{o} with respect to each other.

1.4 Equations of equilibrium of forces:

We can consider a plane of side dx and dy. Let us consider the equilibrium of forces on this plane:

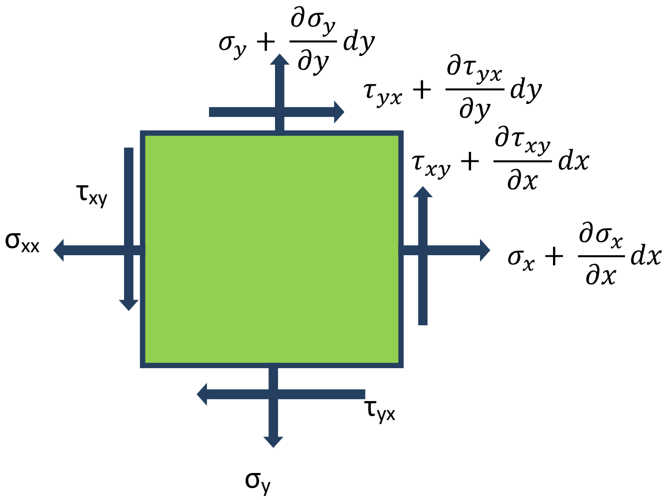

Fig. 2.3.1: Equilibrium of forces on a plane

The equilibrium equations are now written for biaxial stress as:

Along x direction, the force balance gives:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} = 0$$

Along y direction:

$$\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} = 0$$

We have two equations with 4 unknowns.

In order to solve these equations, we need two more equations.

These equations are called compatibility equations.

They are the equivalent stress and equivalent strains, also called effective stress and effective strain

Effective stress is given as:

$\bar{\sigma} = \frac{3}{\sqrt{2}}\tau_{oct}$ whereτ_{oct} $is\ octahedral\ shear\ stress, given\ by$:

$$\tau_{oct} = \frac{1}{3}[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)]$$

Or

$$\bar{\sigma} = \frac{1}{3}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]$$

This equation is in terms of principal stresses.

The effective stress for uniaxial stress is simply equal to the yield strength.

We can define the effective strain as:

$\bar{\varepsilon} = \sqrt{2}\gamma_{oct}$

Or

$$\bar{\varepsilon} = \frac{\sqrt{2}}{3}[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2]$$

In uniaxial stress, we can prove that the effective strain

$$\bar{\varepsilon} = longitudinal\ strain$$

Elasticity

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1. Elasticity:

When external force is applied on a crystalline body, the atoms within get displaced. The atoms get displaced to new positions according to the external force. Atoms respond to the force by changing their displacements according to external force. The extent of atomic displacement depends on the inherent property of the interatomic binding energy. Atoms will occupy new positions such that the external force and internal interatomic force balance each other. This is for small displacements. We can say that the force on a bond is proportional to inter atomic displacement.

1.1 Normal and shear elastic deformations

In crystalline solids the extent to which elastic strain happens is very small, of the order of 0.5% or less. Therefore, we can assume that engineering strain and true strain are identical. Also, we can assume that strain is proportional to stress. This is valid for isotropic materials and for small strains. When a solid gets elastically deformed, it can undergo change in its length, it can undergo shape change or it can undergo rotation.

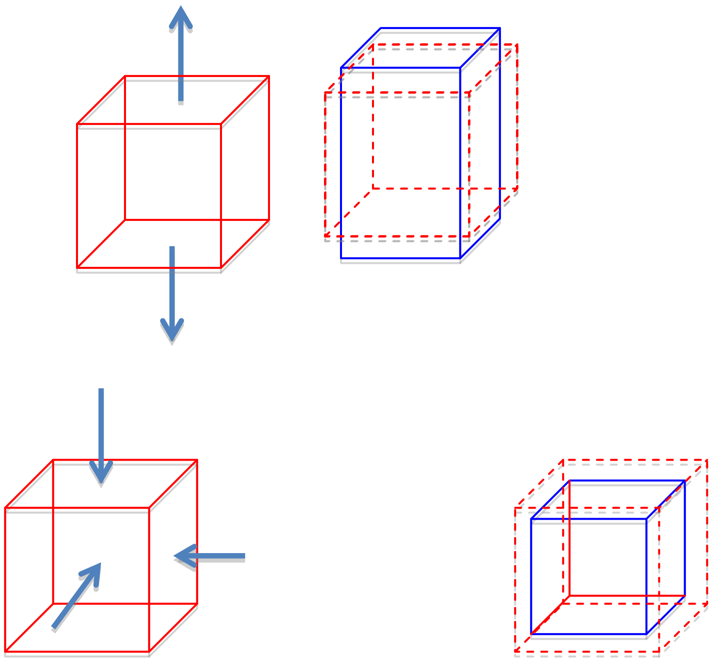
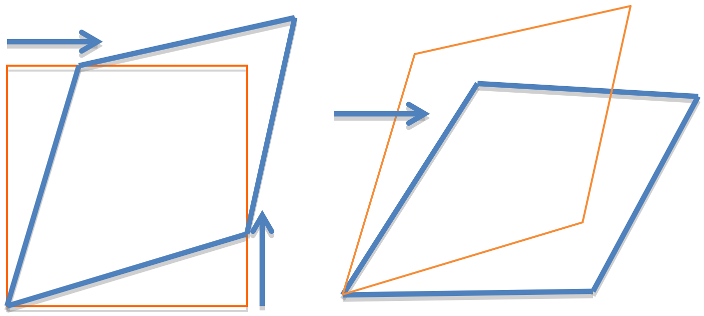


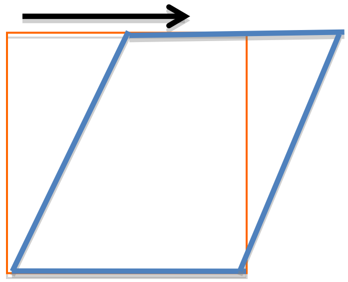
Fig. 3.1.1: Homogeneous Elastic deformations

Shear deformation is caused by shear stress. Shear deformation is dependent on the nature of stress applied. In shear, a material may undergo rotation as well as distortion.



Pure shear

Pure rotation



Simple shear

Fig. 3.1.2: Types of shear deformations

From the above figures we can see that the deformation in simple shear can be equivalent to combined pure shear deformation and rotation.

Shear strain can be produced only by shear stress. Therefore for elastic shear we can write Hooke's law as:

$$\gamma = \tau / G$$

G is shear modulus, which is a function of Elastic modulus.

$G = \frac{E}{2(1+\nu)}$

The bulk modulus B is given from the expression for volumetric strain:

$$\frac{\Delta V}{V} = \frac{\sigma_m}{B}$$

B is also dependent on E

B = $\frac{E}{3(1-2\nu)}$

We understand from this equation the following:

When Poisson's ratio =0, the Bulk modulus B = E/3

If Poisson ratio = ½ then B tends to infinity. This is the case of rigid plastic materials, which are incompressible.

If Poisson ratio is > ½ we get B as negative, which is not possible.

For small strains, we can write:

$$\frac{\Delta V}{V} = \varepsilon_x + \varepsilon_y + \varepsilon_z$$

For tensile deformation, we write for uniaxial state of stress:

$$\varepsilon_x = \frac{\sigma_x}{E}$$

E is Young's modulus or elastic modulus.

Young's modulus is a material property, which depends on the nature of bond and binding energy – energy trough. High melting point materials have high Young's modulus values and vice-versa.

Generally, Young's modulus decreases with increase in temperature from room temperature upto melting temperature.

1.2 Thermal strain:

Suppose a material undergoes change in its temperature, ΔT. Such change in temperature may induce strain in the material. The thermal strain is given by:

e = $\frac{\Delta l}{l} = \alpha \Delta T$ where α is coefficient of thermal expansion.

Typical values of the elastic constants are given in table below.

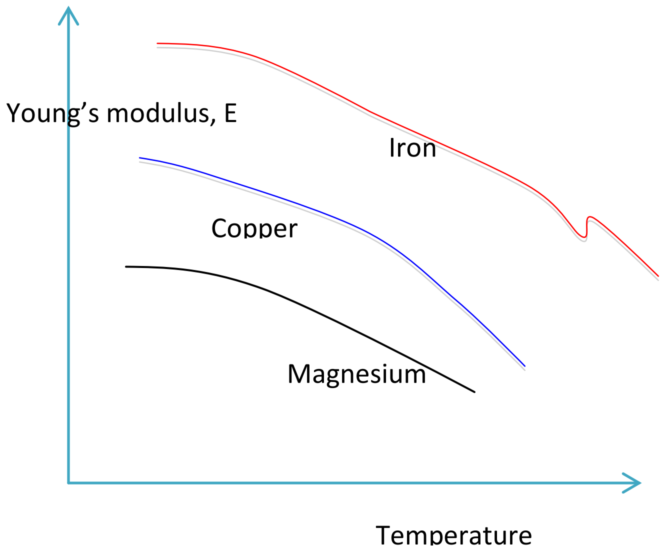


Fig. 3.2.1: Variation of Young's modulus with temperature

Table 3.2.1: Elastic properties of some metals

Material	**E (GPa)**	**Poisson's ratio**	$\alpha\ X\ 10^{-6}\ /^{o}C$
Aluminium	62	0.24	23.6
Copper	128	0.35	16.5
Iron	208	0.29	11.8
MgO	205		9

1.3 Hooke's law for tri-axial state of stress:

In a majority of forming processes, the state of stress encountered by the work piece is triaxial. Some metal forming processes such as rolling, drawing, the state of stress may be biaxial. Both tensile and compressive stresses can occur; both normal and shear stresses can co-exist. In forming processes such as extrusion and deep drawing, state of stress is triaxial.

Suppose the state of stress acting on an element of a body is plane stress, the Hooke's law for such plane stress can be written as followed:

The normal stress $\boldsymbol{\sigma_x}$causes a normal strain which is equal to$\boldsymbol{\sigma_x}$**/E.**

The normal stress acting along y direction causes a lateral strain along x direction, which is given by $-\frac{\upsilon\sigma_y}{E}$

For plane stress the total elastic strain of a body along x direction is:$\varepsilon_x = \frac{1}{E}(\sigma_x - \upsilon\sigma_y)$

Similarly, for y direction:$\varepsilon_y = \frac{1}{E}(\sigma_y - \upsilon\sigma_x)$

The z direction normal strain is now written as:

$\varepsilon_z = -\frac{\nu}{E}\left(\sigma_x + \sigma_y\right)$ This strain in z direction is due to x-direction and y-direction stresses.

For pure shear we write the Hooke's law as:

$\gamma_{xy} = \tau_{xy} / G$

Note: The normal stresses have no effect on shear strain.

Hooke's law can now be written from the above relations:

$$\sigma_x = \frac{E}{1-\nu^2}\,(\varepsilon_x + \nu\varepsilon_y)$$

$$\sigma_y = \frac{E}{1-\nu^2}\,(\varepsilon_y + \nu\varepsilon_x)$$

For triaxial state of stress:

$$\varepsilon_1 = \frac{1}{E}\,[\sigma_1 - \nu(\sigma_2 + \sigma_3)]$$

$$\varepsilon_2 = \frac{1}{E}\,[\sigma_2 - \nu(\sigma_1 + \sigma_3)]$$

$$\varepsilon_3 = \frac{1}{E}\,[\sigma_3 - \nu(\sigma_1 + \sigma_2)]$$

Solving the above equations simultaneously, we get the following stress-strain relations:

$$\sigma_1 = \frac{E}{(1+\upsilon)(1-2\upsilon)}[(1-\upsilon)\varepsilon_1 + \upsilon(\varepsilon_2 + \varepsilon_3)]$$

Similarly the relations for the other two directions can be written.

Volume change or dilatation is defined as change in volume / original volume → e = $\Delta V/V_o$

It can be shown that $e = \varepsilon_x + \varepsilon_y + \varepsilon_z = \frac{(1-2\nu)}{E}(\sigma_x + \sigma_y + \sigma_z)$

1.4 Spherical stress:

If the normal stresses acting in all three directions are equal, the state of stress is called spherical stress.

Spherical stress is given by: $\sigma_o = \sigma_x = \sigma_y = \sigma_z$

The corresponding strain is given as: $\varepsilon_o = \frac{\sigma_o}{E}(1 - 2\nu)$

Due to spherical stress, a cube will expand or contract in size proportionately.

If the spherical stress is compressive, it is called hydrostatic stress.

Note: Hydrostatic stress cannot cause plastic deformation.

For spherical stress, we have $\sigma_x = \sigma_y = \sigma_z = \sigma_o$ and $\varepsilon_x = \varepsilon_y = \varepsilon_z = \varepsilon_o$

Therefore, $e = 3\sigma_o = 3\varepsilon_o = 3\sigma_o \frac{(1-2\nu)}{E}$

For plastic deformation, the volumetric strain = 0 because Poisson’s ratio = 0.5

Under elastic deformation, e can be >0 or e can be < 0.

1.5 Elastic Strain energy:

Strain energy is the energy stored in a material during its elastic deformation. Elastic strain energyis taken to be equal to the work done on the material during elastic deformation. Elastic wok done is equal to the area of elastic portion of stress-strain curve.

U = 1/2Fδ = ½($\sigma A\epsilon dx$) = ½($\sigma\epsilon$) $Volume$

For uniaxial stress, therefore

u = $\frac{U}{Volume} = \frac{\sigma\varepsilon}{2}$

For plane stress condition we can write the elastic strain energy per unit volume due to normal stress, u as:

$$u_1 = \frac{1}{2}\left(\sigma_x\varepsilon_x + \sigma_y\varepsilon_y\right)$$

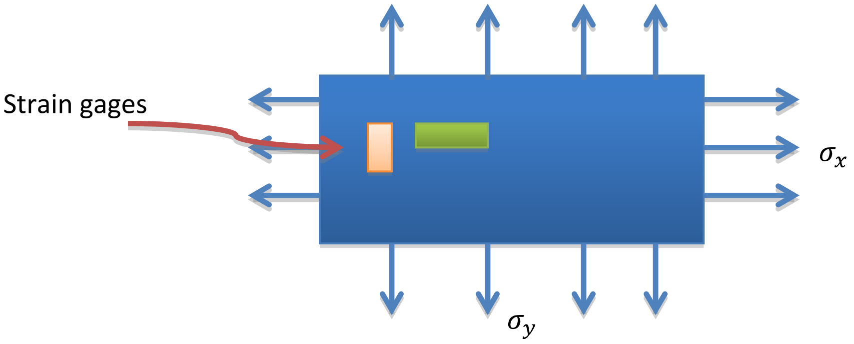
That due to shear is:

$$u_2 = \frac{\tau_{xy}\gamma_{xy}}{2}$$

Total strain energy in plane stress

u = $u_1 + u_2$

Example: A steel plate of rectangular shape with thickness t = 6 mm is subjected to normal tensile stresses along x and y directions. The two strain gages attached on the plate, one in x direction and another in y direction, give the strains as: ε_x= 0.001 and ε_x= -0.0006. Determine the two stresses and the change in thickness of the plate. Assume suitable value of E and Poisson ratio for steel.



Assume E = 200 GPa and **v = 0.3**

The state of stress given is plane stress.

Therefore we can use the stress – strain relations for plane stress:

$$\sigma_x = \frac{E}{1-\nu^2}\,(\varepsilon_x + \nu\varepsilon_y)$$

Substituting the values of the strains and the other parameters, we get the stress:

σ_x= 200X10^3(0.001-0.3X0.0006)/(1-0.3^2) = 180.22MPa

Similarly,

σ_y= -65.93 MPa. (Compressive)

Now we have $\varepsilon_z = -\frac{\upsilon}{E}(\sigma_x + \sigma_y)$ = -1.71X10^{-4}, This strain is contraction strain. There is reduction in thickness.

Plasticity

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1. Plasticity:

1.1 Plastic Deformation, and yield criteria:

1.1.1 States of stress

When a body is subjected to a stress below the yield strength, it will deform elastically. The moment the stress is removed, the body comes to initial position.

In contrast, when the body is stressed beyond the yield point, it will undergo permanent deformation. If it is a ductile material, it will plastically deform continuously with increase in stress applied.

If a certain object is subjected to uniaxial tensile load, it will start yielding – deforming plastically – when the stress reaches the uniaxial yield stress Y.

However, when the state of stress is triaxial, a single shear stress can not be used to predict yielding.

It is the combination of the three stress states which alone can predict yielding.

The relationship among the stresses which predict the yielding of a material is called yield criterion. The inherent assumptions involved in defining the yielding are: the material is isotropic & incompressible, Poisson's ratio equals 0.5 and the hydrostatic or mean stress does not cause yielding of the material. Porous materials like powder metallurgy alloys can be assumed compressible. They have Poisson's ratio less than 0.5.

Commonly, for ductile materials, there are two important yield criteria. They are von Mises yield criterion – also called distortion energy criterion and Tresca criterion also called Maximum shear stress theory.

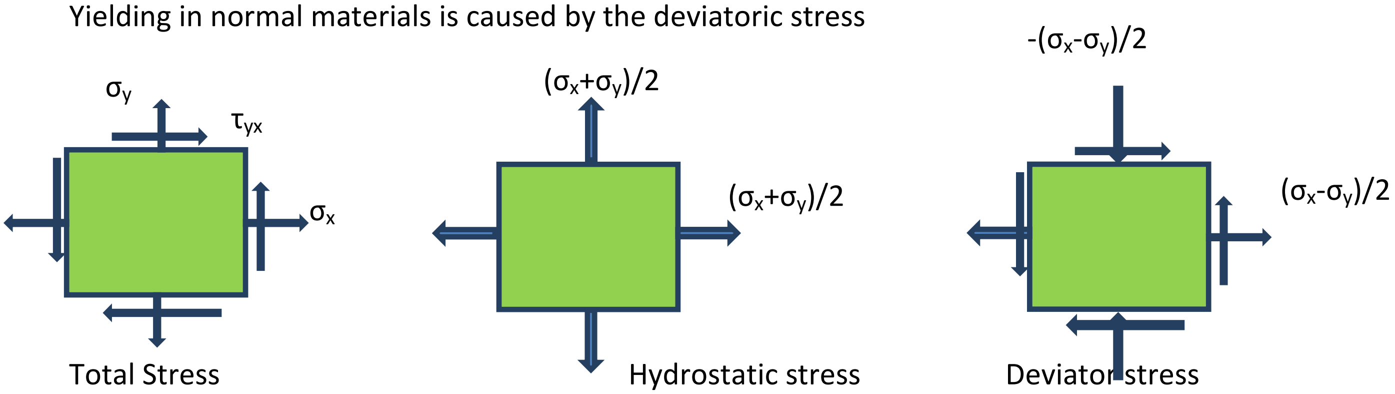
The hydrostatic stress is given by:

$$\sigma_{m} = \frac{\sigma_1+\sigma_2+\sigma_3}{3}$$

Total state of stress at a point can be represented as sum of hydrostatic and deviatoric stresses.

For plane stress, the deviatoric stress is given by: $\frac{\sigma_1-\sigma_2}{2}$etc.

Yielding in normal materials is caused by the deviatoric stress



Total Stress Hydrostatic stress Deviator stress

Fig.1.1.1: States of stress on a plane

From the above figures, we could understand that the given state of biaxial stress can be replaced by a sum of hydrostatic and deviatoric stresses. Hydrostatic stress, though does not influence the yielding, it does increase ductility of a material, when it is applied.

1.1.2 Yield criteria:

Commencement of plastic deformation in materials is predicted by yield criteria. Yield criteria are also called theories of yielding. A number of yield criteria have been developed for ductile and brittle materials.

Tresca yield criterion:

It states that when the maximum shear stress within an element is equal to or greater than a critical value, yielding will begin.

$\tau_{max} \geq k$

Where k is shear yield strength.

Or $\tau_{max} = (\sigma_1 - \sigma_3)/2 = k$ where σ_1 and σ_3 are principal stresses

Or $\sigma_1 - \sigma_3 = Y$

For uniaxial tension, we have k = Y/2

Here Y or k are material properties. The intermediate stress σ_2 has no effect on yielding.

Von Mises criterion:

According to this criterion, yielding occurs when

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2Y^2 = 6k^2$$

For plane strain condition, we have: $\sigma_2 = (\sigma_1 + \sigma_3)/2$

Hence, from the distortion energy criterion, we have $\sigma_1 - \sigma_3 = \frac{2}{\sqrt{3}}Y$ Here, $\frac{2}{\sqrt{3}}Y$ is called plane strain yield strength. Von Mises criterion can also be interpreted as the yield criterion which states that when octahedral shear stress reaches critical value, yielding commences.

The octahedral shear stress is the shear stresses acting on the faces of an octahedron, given by:

$$\tau_{oct} = \frac{1}{3}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$$

According to Tresca criteria we know, $(\sigma_1 - \sigma_3)/2 = k$. Therefore,

$k = \frac{Y}{\sqrt{3}}$

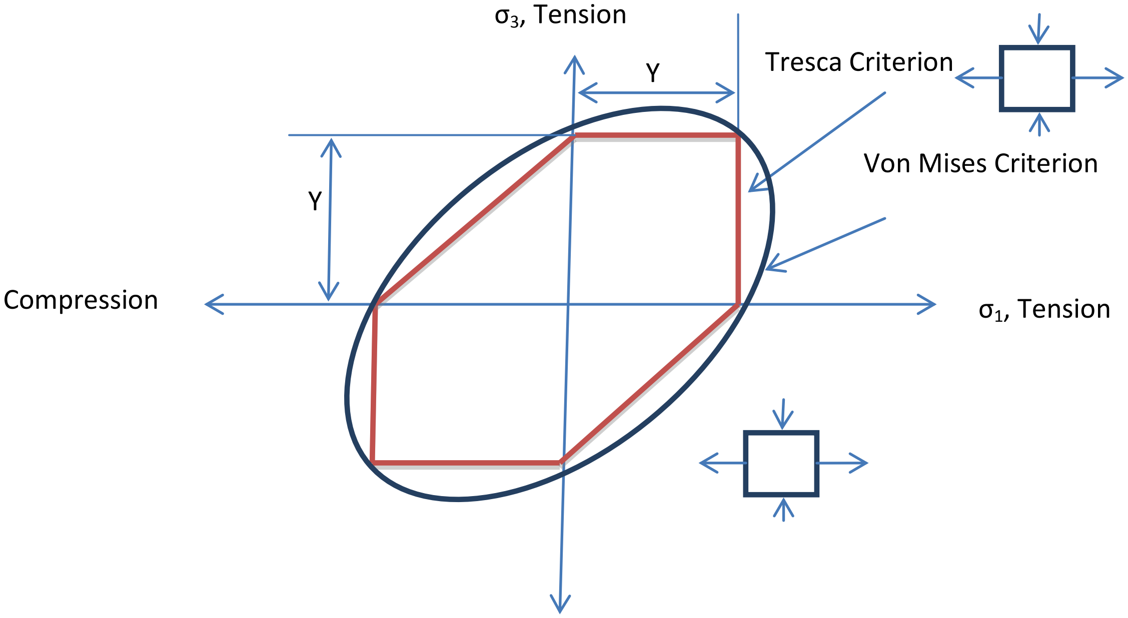


Fig. 1.1.2.1: Yield loci for the two yield criteria in plane stress

Von Mises yield criterion is found to be suitable for most of the ductile materials used in forming operations. More often in metal forming, this criterion is used for the analysis. The suitability of the yield criteria has been experimentally verified by conducting torsion test on thin walled tube, as the thin walled tube ensures plane stress. However, the use of Tresca criterion is found to result in negligible difference between the two criteria. We observe that the von Mises criterion is able to predict the yielding independent of the sign of the stresses because this criterion has square terms of the shear stresses.

1.3 Effective stress and effective strain:

Effective stress is defined as that stress which when reaches critical value, yielding can commence.

For Tresca criterion, effective stress is $\sigma_{eff} = \sigma_1 - \sigma_3$

For von Mises criterion, the effective stress is

$$\frac{1}{\sqrt{2}}\{ [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]\}^{1/2}$$

The factor 1/√2 is chosen such that the effective stress for uniaxial tensile loading is equal to uniaxial yield strength Y.

The corresponding effective strain is defined as:

$$\varepsilon_{eff} = \frac{2}{3}\ (\varepsilon_1 - \ \varepsilon_3)$$

From von Mises criterion:

$$\text{Effective strain} = (\sqrt{2}/3)\{ [(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2]\}^{1/2}$$

For Tresca:

Effective strain = (2/3)$(\varepsilon_1 - \varepsilon_3)$

For uniaxial loading, the effective strain is equal to uniaxial tensile strain.

Note: The constants in effective strain expressions, given above are chosen so that for uniaxial loading, the effective strain reduces to uniaxial strain.

Normal strain versus shear strain:

We know for pure shear: $\sigma_1 = -\sigma_3$ and $\sigma_1 = \tau$

Therefore from the effective stress equation of Tresca we get: Effective stress = $2\sigma_1 = 2\tau_1$

Similarly using von Mises effective stress, we have

Effective stress = $\sqrt{3}\sigma_1 = \sqrt{3}\tau_1$

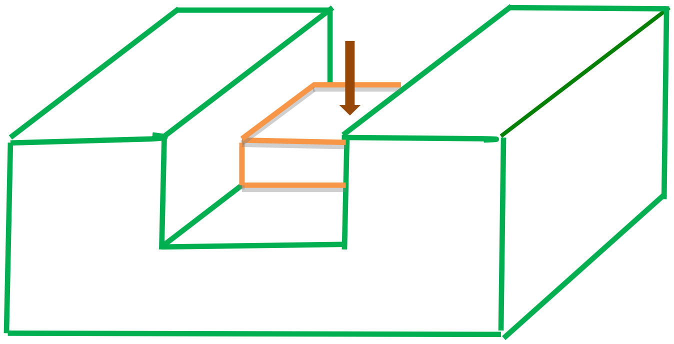


Fig. 4.3.1: A plane strain compression forging process

1.4 Flow rule:

Stress-strain relations for plastic deformation are given by the flow rules, as we can not assume linear relationship between them.

For triaxial stress the flow rules are given by:

$$d\varepsilon_1 = \frac{d\bar{\varepsilon}}{\bar{\sigma}}(\sigma_1 - 0.5(\sigma_2 + \sigma_3)$$

$$d\varepsilon_2 = \frac{d\bar{\varepsilon}}{\bar{\sigma}}(\sigma_2 - 0.5(\sigma_1 + \sigma_3)$$

$$d\varepsilon_3 = \frac{d\bar{\varepsilon}}{\bar{\sigma}}(\sigma_3 - 0.5(\sigma_1 + \sigma_2)$$

For triaxial stress, we can represent the yielding by means of three dimensional representation called yield surface. The yield surface for von Mises criterion is a hollow cylinder which is oriented at equal angle with reference to the three reference axes x, y, z. Here we assume that each axis represents one of the three principal stresses.

Yielding commences when the triaxial stress acting on a body reaches the surface of the cylinder. If the material is a work-hardening material, the cylinder expands as more plastic deformation happens, due to increase in stress required for plastic flow. According to Drucker, the total strain vector should always be normal to the yield surface at any point which corresponds to a given state of stress. Further, it is known that the axis of the yield cylinder is the hydrostatic stress, σ_m. As the total strain is given to be normal to yield surface, the hydrostatic stress, which is normal to deviatoric stress. Deviatoricstress is acting along the direction of total strain vector. Therefore, mean stress can not cause yielding, because it is orthogonal to deviatoric stress.

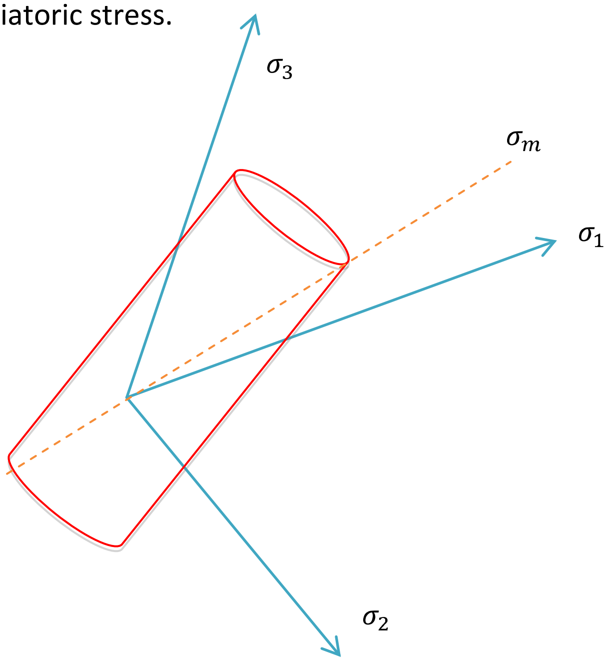
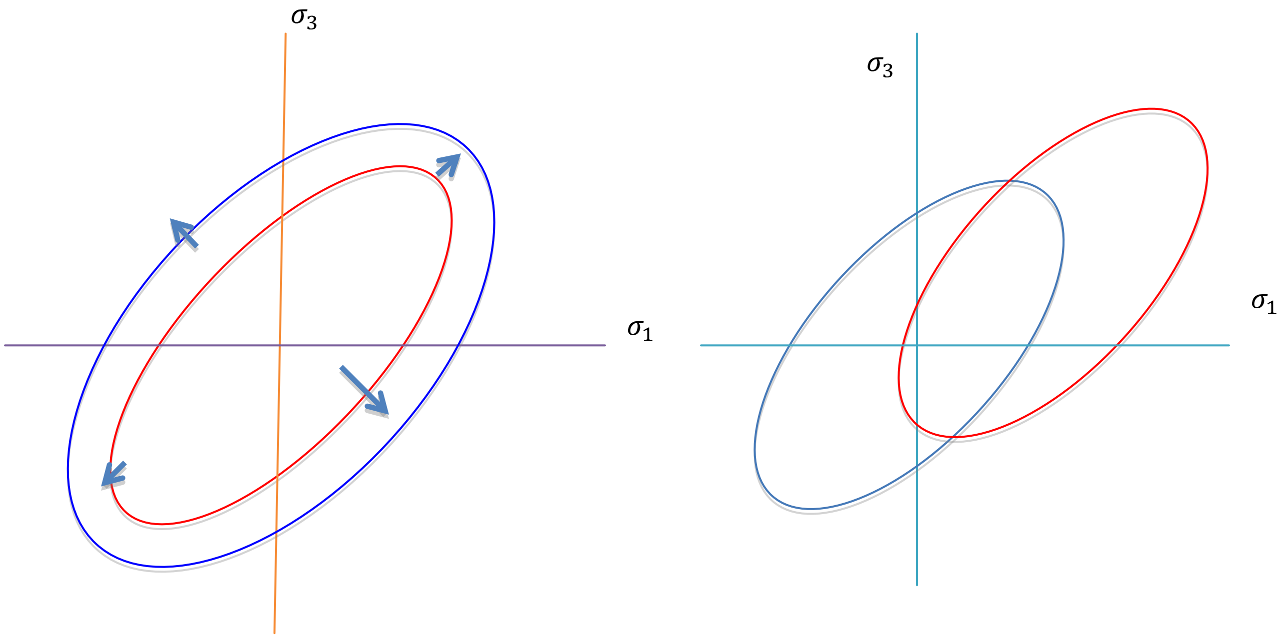


Fig. 1.4.1: Yield surface for a material which obeys von Mises yield criterion

1.5 Work hardening

In plastic deformationof some materials, the material becomes stronger after getting worked upon. Its yield strength increases after plastic working. This is known as work hardening. There are two ways of accounting for the work hardening. They are: Isotropic work hardening, in which yield strength increases uniformly in all directions. The yield locus gets stretched out uniformly all around. The other way is kinematic hardening in which the yield stress does not undergo any increase. On the other hand the yield locus gets shifted in the direction of strain. Predominantly, in plasticity we tend to account isotropic hardening alone.



Isotropic work hardening *Kinematic work hardening*

Fig. 1.5.1: Effect of two types of work hardening on yield locus

Example: Consider a body which is stressed so that it yields. A shear stress of 200 MPa is acting on octahedral plane. What would be the yield strength of the material under tension and shear?

Solution:

We are given the octahedral shear stress. The octahedral shear stress is given by:

$$\tau_{oct} = \frac{1}{3}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$$

Taking $\sigma_2 = \sigma_3 = 0$ and solving for σ_1, we get:

$\sigma_1 = 424.26$ MPa. This is the tensile yield strength value required.

According to von Mises criterion, we have the relation between tensile and shear yield strengths as:

k = Y/$\sqrt{3}$ = 244.96 MPa. This is the required shear yield strength.

Analysis of forming- Slab Method

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1. Analysis of forming - Slab Method

Forming of materials is a complex process, involving either biaxial or triaxial state of stress on the material being formed. Analysis of the forming process, therefore is highly involved. Prediction of forming load in a particular process is rather empirical. However, fairly accurate methods have been developed in order to predict the forming process and process parameters. Some of the early methods of forming analysis include slab analysis, slip line field analysis, upper bound analysis etc. With the availability of high speed computers, we can depend on finite element method for accurate predictions of forming loads. Numerous metal forming softwarehave been developed based on finite element procedures for complex shapes with more realistic boundary conditions. In this lecture we will discuss the simple slab method of forming analysis, with a typical example.

Slab method is a simple analytical procedure based on principles of mechanics. We can assume a simple relation between forming load and material flow stress in the form: F = k$\bar{\sigma}$A, where k is an empirically determined constant which takes into account friction, redundant deformation etc. The general methodology involved in slab method can be stated as follows: First the material under deformation is sliced into infinitesimally small portions. Then force balance is made on the small element. From force balance a differential equation in terms of the forming stress, geometric parameters of the billet and friction coefficient is formulated. This differential equation is solved with suitable boundary conditions. The solution gives us the required forming stress. This method may involve some simplifying assumptions. Hence this method may be considered approximate. Moreover, it may not be easy to apply this method for more complex forming processes, such as impression die forging. Slab method is developed with the assumption that the material flow is homogeneous during forming.

1.1 Slab method - Upsetting of a ring

Let us try to understand the slab method of forming analysis with the help of a simple example. Sliding or Columbic friction often occurs at the material tool interface. As a result of friction the forming load is enhanced. The flow of material is also non-uniform due to friction. Another type of friction condition, namely, shear friction or sticking friction could be convenient to consider in the analysis. In shear friction model, we assume the frictional shear stress to be proportional to shear yield strength of the material. Thus we have: $\tau = mk$, where m is friction factor and k is shear yield strength. The following assumptions are the basis of the slab analysis:

1. The reference axes are in the directions of the applied stresses
2. Friction does not cause non-uniform deformation. Therefore material is assumed to deform homogeneously – a plane remains a plane after deformation.

Consider the homogeneous deformation of a ring shaped specimen subjected to upsetting force. Let us assume shear friction at tool-material interface. The ring compression process is widely used for finding the coefficient of friction for given condition of friction. Consider an elemental portion of the ring specimen and the various stresses on this element. The following diagram shows the stresses acting on the elemental part of the ring.

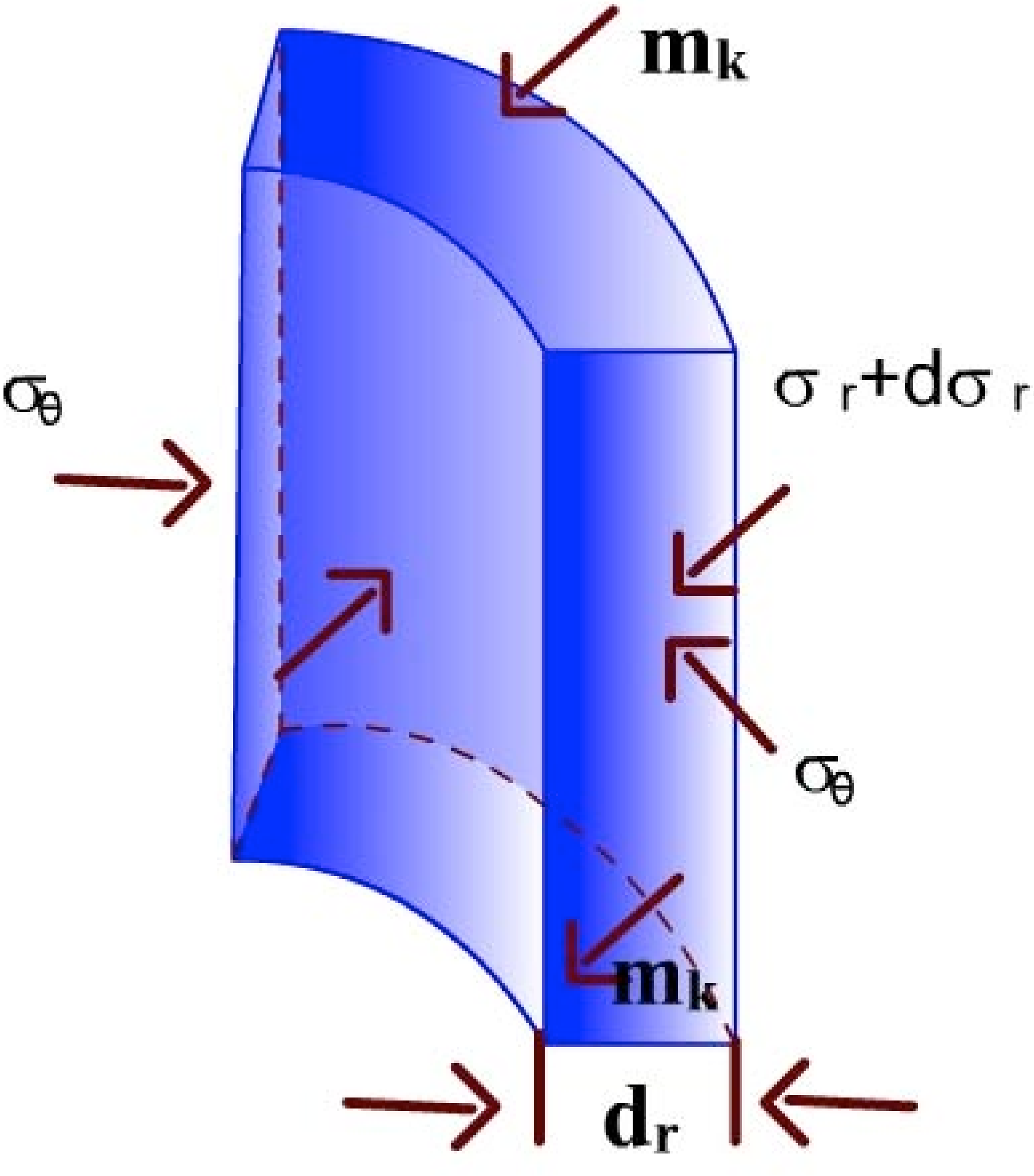

Fig. 5.1.1: Stresses acting on elemental ring subjected to upsetting

Consider a small sector of an elemental ring of radius r, radial thickness dr, height h and the angle of the sector as $d\theta$. The ring is subjected to upset force F, which is to be determined.

The various stresses acting on the sector are:

Radial stresses $\sigma_r, \sigma_r + d\sigma_r$The corresponding forces are: σ_rrdθh and $(\sigma_r + d\sigma_r)$(r+dr)dθh

Hoop stress σ_θ The corresponding force is given by: σ_θ dr h sin$\frac{d\theta}{2}$

Frictional shear stress mk The corresponding force is: mk r drdθ

The arc length of the sector element is given by: rdθ

We can also note that for uniform deformation of the ring, $\sigma_\theta = \sigma_r$

There exists a neutral radius in the ring, such that the material deformation happens towards the axis for radii less than the neutral radius. There is a decrease in diameter of the ring.

For radii greater than the neutral radius, the material flow is away from the axis-axially outward. This condition exists because of friction. Therefore, the friction force is observed to act axially outward within the neutral section. It acts radially inward in sections beyond the neutral section.

The force balance along the radial direction gives:

σ_rrdθh $-(\sigma_r + d\sigma_r)$(r+dr)dθh + 2σ_θ dr h sin$\frac{d\theta}{2} \mp$ 2mk r drdθ = 0

Dropping higher order terms, and applying $\sigma_\theta = \sigma_r$

$d\sigma_r = \mp 2(m/h)k\, dr$

We need to solve for σ_z the axial stress for upsetting the ring

We can apply Tresca yield criterion in order to replace σ_r in the above differential equation.

Let us assume that the two principal stresses acting on the ring are: σ_r and σ_z

Therefore, we have:

$\sigma_z - \sigma_r = Y$

Replacing dσ_r with dσ_z, above we have:

$d\sigma_z = \mp 2(m/h)k\, dr$

Integrating once, we get:

$\sigma_z = \mp 2(m/h)k\, r + C$

For solving the constant C we could apply the following boundary conditions:

iAt r = R_i, σ_r = 0 and σ_z = Y (From Tresca criterion)

ii At r = R_0, σ_r = 0 and σ_z = Y

We get the constant C as:

C = $Y - 2(m/h)k R_i$

Or

C = $Y + 2(m/h)k R_o$

Substituting for C in the general solution, we get:

σ_z = Y + 2(m/h)k(r-R_i) ---------- for the section inside the neutral section

and

σ_z = Y + 2(m/h)k(R_o-r) ---------- for outside neutral section

For continuity of the stresses, we can take the neutral section radius as:

$R_n = (\frac{R_i+R_o}{2})$

Also note that $k = \frac{Y}{\sqrt{3}}$ according to von Mises yield criterion

One can get the average upset force, F from the local stress as followed:

$$F = \int_{R_i}^{R_n} \sigma_z \, 2\pi r dr + \int_{R_n}^{R_o} \sigma_z \, 2\pi r dr$$

$$\boxed{F = (1 + \frac{1}{2\sqrt{3}}\frac{m}{h}(R_o - R_i))\bar{\sigma}A}$$

In the above equation the bracketed term represents the factor which accounts for friction effect during the forming. The limitation of uniform deformation assumption in slab method is overcome in another method of analysis called slipline field analysis, which is discussed in the next lecture.

The upset force is found to vary linearly with the friction factor m, as observed from the above equation. Further, we also note that the forming force required increases with reduction in height of the ring. Rings of smaller height require greater forming force as compared to rings of larger height. This is expected because the redundant deformation zone extends towards centre for rings of smaller height.

Ring compression test is a simple test for determination of friction factor or the coefficient of friction. It can also be used for studying the lubrication characteristics of different lubricants.

Analysis of forming- Slipline Field Method

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1. Analysis of forming –Slipline Field Method

1.1 Methodology of slipline field analysis:

Slab analysis of the forming process is considered approximate due to the assumption of homogeneous deformation of material. Slipline field analysis is more accurate as it considers the non-homogeneous deformation also. This method is widely applied for forming processes such as rolling, strip drawing, slab extrusion etc. Slipline field analysis is based on the important assumptions that the deformation of material is plane strain type, no strain hardening of the material, constant shear stress at interfaces, the material is rigid plastic.

The general methodology of this analysis can be described by the following steps:

First differential equations in terms of mean stress and deviatoric stress for plane strain deformation are formulated

Slipline field is constructed graphically out of orthogonal maximum and minimum shear lines.

From known stress at some point, the integral constants are determined. From this the forming load can be found.

Before we proceed to understand the methodology of the analysis a few definitions should be considered.

What are sliplines? They are planes of maximum shear, which are oriented at 45 degrees to the axes of principal stresses. Maximum and minimum slip lines are orthogonal.

What is plane strain deformation? It is a type of plastic deformation in which the material flow in one of the three principal directions is constrained. The material strain in the third direction is zero. This is possible by the application of a constraint force along the third direction. All displacements are restricted to xy plane, for example. Examples for this type of deformation include strip rolling, strip extrusion etc.

Constraint to deformation along the third axis could be introduced either through the die wall or through the rigid material adjacent to deforming material, which prevents the flow.

The basis for slipline field analysis is the fact that the general state of stress on a solid in plane strain deformation can be represented by the sum of two types of stresses, namely the mean stress and the pure shear stress.

For plane strain condition we have $\sigma_2 = \frac{\sigma_1+\sigma_3}{2}$

We can write the Tresca criterion for plane strain as: $\sigma_1 - \sigma_3$ = 2k

For plane strain deformation we have the equilibrium of stresses written in differential form as:

$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial x} = 0$ ------------------- 1

$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} = 0$ ------------------2

These two differential equations will be transformed into two algebraic equations along a changed coordinate system, namely, along two directions of maximum shear. Then they can be solved subjected two suitable boundary conditions.

Consider the plane strain state of stress acting on x-y plane. Let σ_x ,σ_y and τ_{xy} be the stresses acting in this plane.

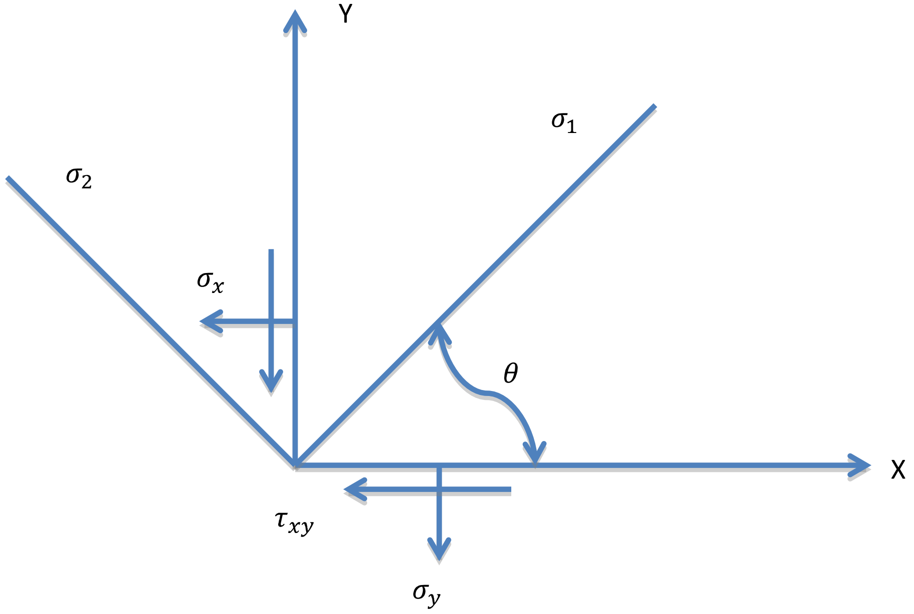

Fig. 6.1.1: Stresses in Plane strain condition

For plane strain condition, we have:

$\sigma_1 - \sigma_3$ = 2k ----------3

and

$\sigma_2 = \frac{\sigma_1+\sigma_3}{2}$ = -p (hydrostatic stress) ---- 4

For the stress conditions shown above, we can write:

$\sigma_x = \frac{\sigma_1+\sigma_3}{2} + \frac{\sigma_1-\sigma_3}{2} cos2\theta$ -----------------5

$\sigma_y = \frac{\sigma_1+\sigma_3}{2} - \frac{\sigma_1-\sigma_3}{2} cos2\theta$ ----------------6

$\tau_{xy} = \frac{\sigma_1-\sigma_3}{2} sin2\theta$ -----------------7

Now substituting 3 and 4 in 5, 6 and 7 we get:

σ_x = -p + kcos2θ -------------- 8

σ_y = -p - kcos2θ ---------- 9

τ_{xy} = ksin2θ ---------------- 10

Substituting the expressions for σ_x, σ_y and τ_{xy} from 8,9, 10 into the differential equations 1 and 2

We get:

$$\frac{\partial(-p)}{\partial x} - 2ksin2\theta\frac{\partial\theta}{\partial x} + 2kcos2\theta\frac{\partial\theta}{\partial y} = 0 \qquad \text{----- 11}$$

$$\frac{\partial(-p)}{\partial y} + 2kcos2\theta\frac{\partial\theta}{\partial x} + 2ksin2\theta\frac{\partial\theta}{\partial y} = 0 \qquad \text{---------- 12}$$

Let the x and y axes be rotated through 45°, that is, $\theta=\frac{\pi}{4}$

Then the equations 11 and 12 become:

$$\frac{\partial(p+2k\theta)}{\partial x} = 0 \qquad \text{------ 13}$$

$$\frac{\partial(p-2k\theta)}{\partial y} = 0 \qquad \text{--------- 14}$$

If the directions x and y are taken to be directions of maximum shear, denoted as directions $\alpha\ and\ \beta$,

Then we have:

$$\frac{\partial(p+2k\theta)}{\partial\alpha} = 0 \qquad \text{------ 15}$$

$$\frac{\partial(p-2k\theta)}{\partial\beta} = 0 \qquad \text{--------- 16}$$

Equations 15 and 16 represent the two differential equations transformed to the directions of maximum shear, $\alpha\ and\ \beta$.

Here the directions $\alpha\ and\ \beta$ are called slip lines (lines of maximum shear)

Therefore, we may now conclude from 15 and 16 that:

p+2kθ = constant along α line and = f(α) ------ 17

Similarly, p -2kθ = constant along β line and = f(β) ------18

Or we can write: p = -2k$\Delta\theta$ along α lines

And p = 2k$\Delta\theta$ along β slip lines

The above equations mean that the pressure p changes by an amount equivalent to change in the angle as one moves along the slip lines.

The following conditions are to be remembered while establishing the slip line field:

The stress normal to a free surface is a principal stress and hence the slip lines meet the free surface at 45°.

$\alpha\ and\ \beta$lines always meet at 45° on a frictionless surface.

They meet at 0° and 90° on a surface with sticking friction

Slip happens along the slip lines as there is maximum shear along the slip lines. Further, along the tangent to the slip lines there is a discontinuity of velocity.

The angle between the intersection of one type of slip line with the other type of slip line remains the same all along the slip line.

The radii of curvature of the intersecting slip lines ($\beta\ lines$) along one type of slip lines ($\alpha\ lines$) change by an amount equal to their distances traversed.

1.2 Illustration of the slip line field analysis:

Consider the extrusion of a strip through a square die. Assume a reduction of 50%. See figure below

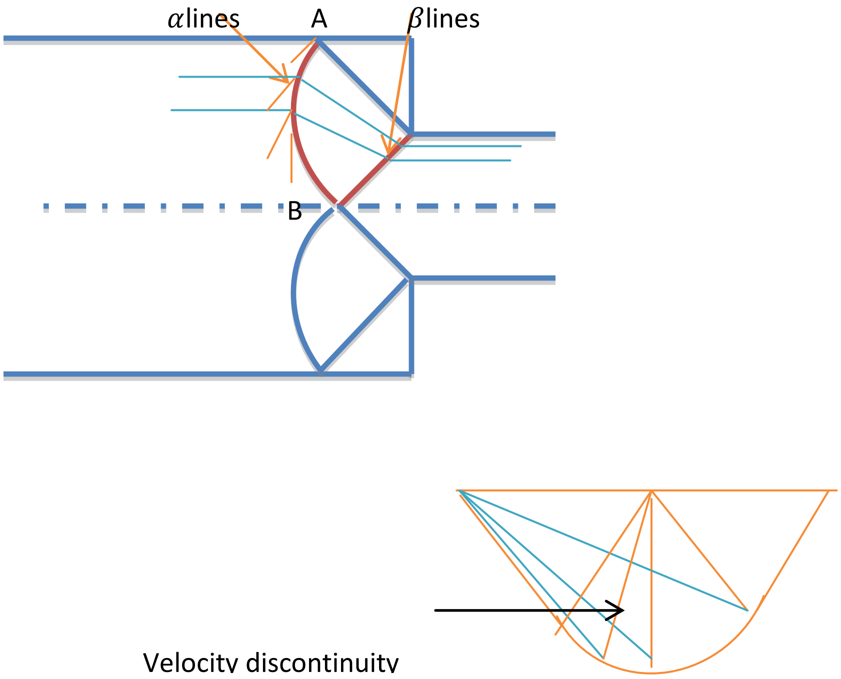

Fig.1.2.1: Slip lines and hodograph for axisymmetric extrusion

The slip lines are shown as radial and circular lines in the figure. The deformation field is symmetrical about center line. Therefore we may analyse one half of the deformation region. The hodograph – velocity diagram is also shown above.

Material undergoes velocity discontinuity along $\alpha\ lines$. The velocity discontinuities are shown in hodograph. Similarly the velocity vectors are shown in hodograph as lines radiating from top left corner of the hodograph.

The horizontal line in hodograph represents the velocity vector of the particles before they enter the $\alpha\ line$.The total length of the horizontal line in hodograph represents the exit velocity of the material, which is twice the initial velocity in this case – because we assume the reduction as 50%.

We need to find the punch pressure p. Stresses acting along the $\beta\ line$ are shear stress k and hydrostatic pressure p.

Along the $\alpha\ line$, we can write: $p+2k\theta = \text{constant}$

Now the pressure at point A, is given by: $p_A - p_B = 2k(\theta_A - \theta_B) = 2k\frac{\pi}{2}$

We find that $p_B = k$ because, the $\beta\ line$ is inclined at 45° with the axis (No normal stress acts).

Therefore, the punch pressure, $p_A = k(1+\pi)$

The total extrusion pressure is given by: $p_e = k(1+\frac{\pi}{2})$

From the punch pressure and area of the billet we can calculate the punch force.

Analysis of forming –Upper bound Analysis

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1. Analysis of forming –Upper bound analysis

Slip line field analysis has limited application in forming in view of its applicability to plane strain deformation only. A more accurate and general analysis for determination of forming load is the application of limit theorems. There are two limit theorems, upper bound and lower bound. The lower bound theorem is not widely used for forming because it under estimates the forming load. Upper bound analysis overestimates the forming load. Therefore, upper bound analysis is widely used for accurately predicting forming loads. It is applicable to almost all types of forming. One should get the solution to the forming problem so that the solution should be kinematically and statically admissible. Kinematically admissible means the velocity field chosen should satisfy the expected boundary conditions for the forming process as well as satisfy the requirement of incompressibility. In upper bound we expect the kinematically admissible condition to be satisfied by the solution. Rigid body motion is assumed for the deforming material –in the form of triangular elements. This could satisfy the requirement of kinematically admissible velocity field. The velocities of various parts of the deforming material are represented in diagrams called hodographs. One has to choose a trial velocity field such that it is closer to the actual velocity field expected in the forming process.

1.1 Upper-bound theorem:

It states that for a given set of velocity fields, the velocity field which minimizes the total energy is the nearest to the actual solution. In other words, this velocity field minimizes the function:

The upper-bound theorem can also be stated in a different way. It states that the estimate of the force obtained by equating the internal energy dissipation to external forces is equal to or greater than the correct force. We should assume a suitable flow field for the deformation.

In short, the field which minimizes the energy dissipation rate, given below, is the required field:

$$\dot{E} = \int_V \bar{\sigma}\,\dot{\bar{\varepsilon}}\,dV + \int_{Sd} k\,|\Delta V_t|\,dS + \int_{Sf} mk\,|\Delta V_s|\,dS = \text{Forming Load X Velocity of punch/die} \quad \text{-------- 1}$$

The first term on right hand side is the rate of work done due to plastic straining, the second term is the rate of energy dissipated in internal velocity discontinuity and the third term represents power consumed for friction. Generally for continuous velocity field the second term can be ignored.

In a nutshell, we could say that the rate of external work done in the process is equal to internal power required for homogeneous deformation plus rate of work done in shear or redundant deformation plus rate of work done for overcoming friction. In the following example we will illustrate the methodology for determination of work done in shear deformation of a material. Subsequesntly, we will know how forming load could be determined applying the upper bound theorem.

1.2 Example: Determination of shear work done

The general methodology of the analysis involves, first, assuming a flow filed within the deforming material that will suitable reflect the material flow. The flow field is otherwise called velocity field. Next step is to find the rate of energy consumption or the rate of work done for this flow field. Finally, the external work done is equated to the energy for the flow field. From this we can solve for the forming load.

The shear work or the rate of work in shearing a material can be determined easily from an assumed flow field for the forming process. Fist we must assume a suitable velocity field. We must draw the velocity vector diagram, called hodograph for the assumed flow field, which should be kinematically admissible. Once drawn, we can determine the shear work done or energy dissipated in shear. Equating the energy dissipated in shear to the rate of external work done, one can determine the forming force (under ideal condition). This analysis is based on the assumptions: deformation is homogeneous without work hardening, there is no friction or there is sticking friction at interface and the flow is two dimensional.

Let us consider a simple example to illustrate this approach. Consider a rigid element of the deforming material, pqrs, which is along the x axis. See figure below. Let this element have a velocity of V1. Let this element pass through a plane yy. After passing through the plane the element changes direction, attains a velocity of V_2. It also gets distorted to a new shape, p'q'r's'. The plane yy can be called shear plane, as it causes the shear of the material.

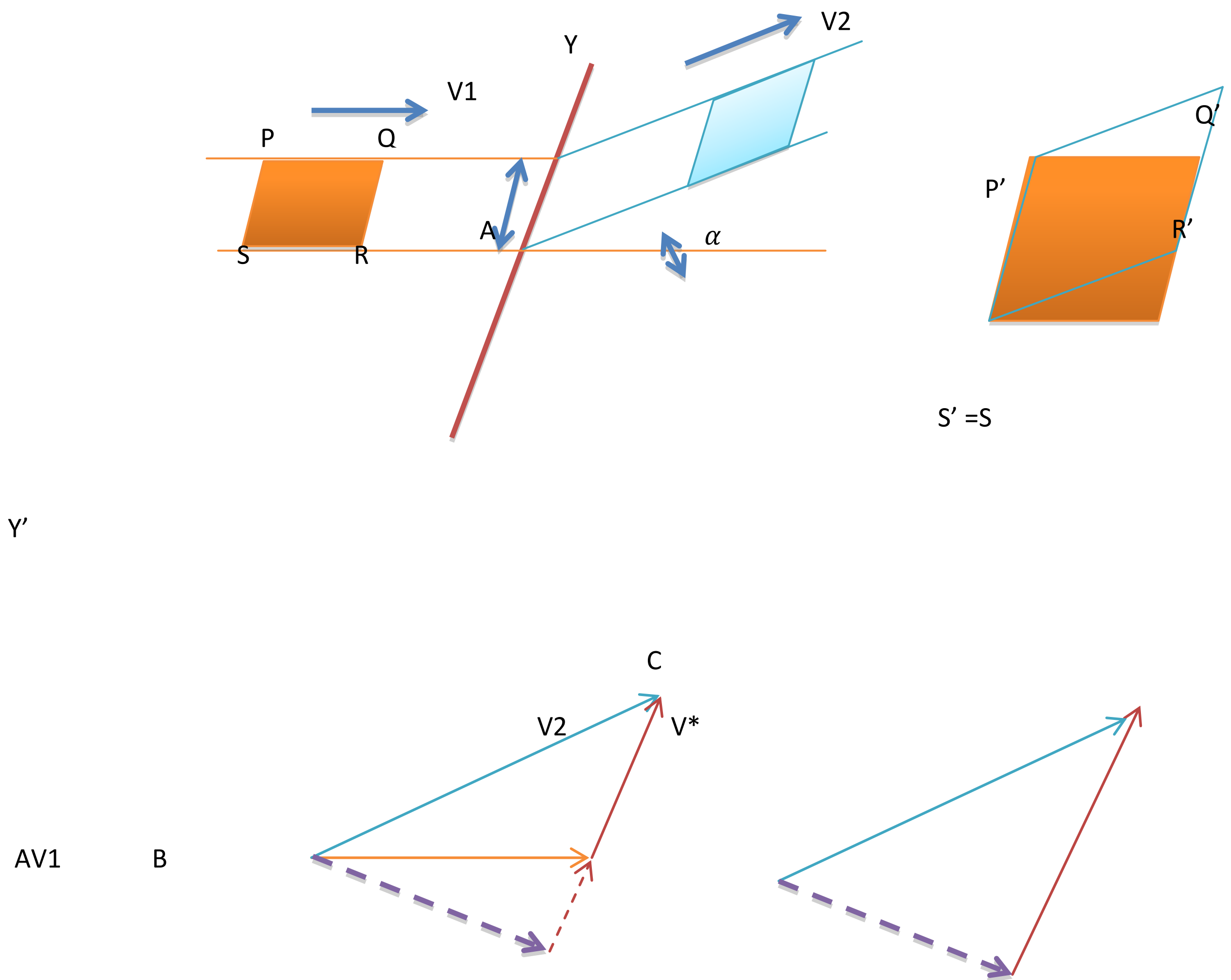

Fig. 7.2.1: Shear deformation of a plane element through the shear plane y-y' and hodograph

Let α be the angle by which the element gets sheared. Let the thickness of the element perpendicular to the plane of the paper be unity. A is the height of the element parellel to the plane of shear. V1 and V2 are the velocities before and after shear.

The hodograph or the velocity vector triangle is shown above. The velocities V1 and V2 can be resolved along the line of shear YY' and perpendicular to the line YY'. Note that the perpendicilar components are equal. The components of velocities along YY' are not equal. This gives raise to velocity discontinuity. The difference in the velocity components along the line YY- is called velocity discontinuity. It is denoted as V*.

The volume rate of flow of the material should remain constant through the process.

Therefore, we have the perpendicular velocity components equal.

Volume flow rate = V_1 X A (Unit depth) ------ 2

Shear work done per unit volume of the material = w = $\tau\gamma$ ---- 3

Let τ = k the shear yield strength of the material.

Shear strain of the deformed material can be written as γ = R'R/RS = V*/V1 (By similarity of the triangles ABC and S'RR')

Total power in the shear deformation is:

w X volumetric flow rate = (kV*/V_1)(V_1 X A) = kV*A ------ 4

A can be called the length corresponding to the velocity discontinuity along the tangential direction to the plane of shear.

If multiple lines of velocity discontinuity are assumed for the deformation zone,

The rate of work done in shear deformation can be written as:

$\dot{w} = \sum kA_i {V^*}_i$ ------5

This method can be extended to complex flow geometries such as extrusion, by assuming triangular or polygonal elements of shear, each element assumed to move as a single rigid body.

1.3 Example to illustrate the general upper bound solution:

According to upper-bound theorem the following relation could be used for calculation of forming load for any forming operation, if we could assume a suitable velocity field or deformation field.

$\dot{W}$ = work done for homogeneous deformation + work done for shear deformation + work done in friction = $\dot{w}_h + \dot{w}_s + \dot{w}_f = \int_V \bar{\sigma}\,\dot{\bar{\varepsilon}}\,dV + \int_{Sd} k\,|\Delta V_t|\,dS + \int_{Sf} mk\,|\Delta V_s|\,dS$ ------ 6

Let us apply this principle for a simple forming process of plane strain compression of a rectangularplate. Let h be the height of the plate at any instance. Let Vd be the velocity of the punch or die.

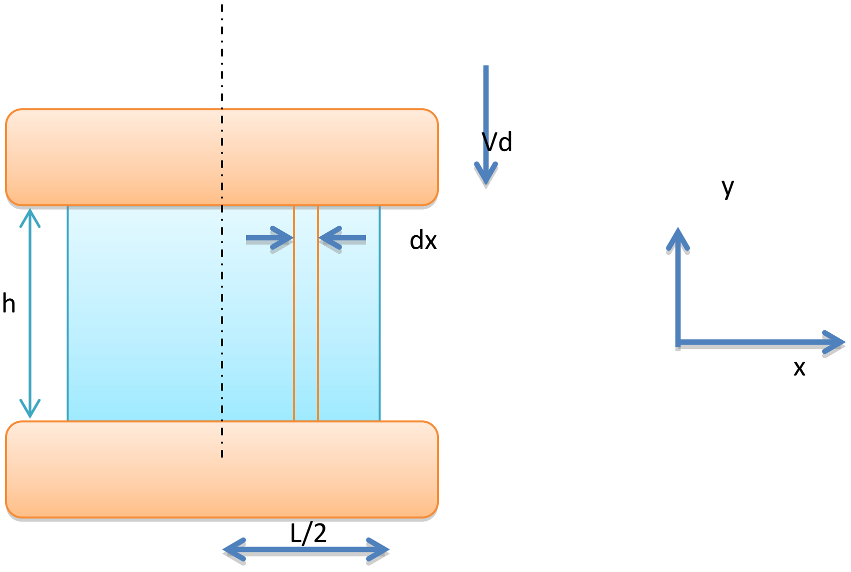

Figure 7.3.1: Plane strain upsetting

Consider an elemental strip of height h and thickness dx, width of unity. The upper die moves down with a velocity of Vd. The elemental strip is located at a distance x from the axis of compression. Assume the interfacial friction to be of sticking friction. So then the frictional shear stress is given by: τ = mk.

The height strain of the element can be written as: dh/h.

Strain rate along the height direction is given by: dh/h/dt = Velocity/h

Therefore, $\dot{\varepsilon}_h$ = Vd/h (For linear variation of velocity along the height)

Now, we have $\dot{\varepsilon}_h + \dot{\varepsilon}_x + \dot{\varepsilon}_z = 0$

However, we have $\dot{\varepsilon}_z = 0$ for plain strain compression

Therefore, we have: $\dot{\varepsilon}_x$ = -V_d/h

Now the velocity of material along x direction, $V_x = \dot{\varepsilon}_x$ x = $\frac{V_d}{h}$x

Let us now write down the individual terms in equation 6

Rate of work for homogeneous deformation:

$$\dot{w}_h = \int_V \bar{\sigma}\,\dot{\bar{\varepsilon}}dV = \bar{Y}\frac{V_d}{h}\,Lh = \frac{2}{\sqrt{3}}Y\frac{V_d}{h}\,Lh \qquad \text{---------}\ 7$$

Rate of shear work $\dot{w}_s$= 0

Rate of friction work $\dot{w}_f$ = $\int_{Sf} mk$ |ΔV_s|dS = 2 $\int_0^{L/2} mkdx \frac{V_d}{h} x$ = 2m$\frac{Y}{\sqrt{3}} \frac{V_d}{h} \frac{L^2}{8}$

The total rate of work = $\frac{2}{\sqrt{3}} Y \frac{V_d}{h}\ Lh$ + 2m$\frac{Y}{\sqrt{3}} \frac{V_d}{h} \frac{L^2}{8}$

We can equate the total rate of work to rate of external work.

Rate of external work done by the forming load F = F V_d

Therefor, the forming load = F =($\frac{2}{\sqrt{3}} Y\ Lh$ + m$\frac{Y}{\sqrt{3}} \frac{L^2}{4}$)$\frac{1}{h}$

Now, we can write the average forming pressure or die pressure, p as:

$p_{av} = \frac{F}{L}$ = $\frac{2}{\sqrt{3}} Y$(1 + m$\frac{L}{8h}$)

Or$\boldsymbol{\frac{p_{av}}{\bar{Y}} = (1 + m\frac{L}{8h})}$

Thus we are able to apply the upperbound analysis for a simple upsetting problem.

Introduction and classification of forging processes

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1. Introduction and classification of forging processes

1.1 Introduction:

Bulk deformation processes involve shaping of materials to finished products which have small surface area to thickness or surface area to volume ratio. Sheet metal forming produces parts having large surface area to thickness ratio. In sheet metal forming thickness variations are not desirable. Examples for sheet metal forming are: beverage cans, automobile body etc.

Bulk forming processes may be primary processes such as rolling of ingot to blooms or billets, in which the cast metal is formed into semi-finished raw material. In secondary forming, the raw materials, such as blooms, billets are converted into finished parts such as gears, wheels, spanners etc.

Rolling, forging, extrusion and drawing are bulk forming processes. The present module describes the salient aspects of forging process.

1.2 Forging:

In ancient times, people employed forging for making coins, jewelry, weapons,

Forging is a deformation processing of materials through compressive stress. It is carried out either hot or cold. Hot forging is done at temperatures above recrystallization temperatures, typically 0.6 T_m, or above, where T_m is melting temperature. Warm forging is done in the temperature range: 0.3 T_m to 0.5 Tm. Cold forging has advantages such as good surface finish, high strength and greater accuracy. Hot forging requires lower loads, because flow stress gets reduced at higher temperatures. Strain rates in hot working may be high – 0.5 to 500 s_{-1}. Strains in hot forging are also high – true strains of 2 to 4. Are common.

Typical applications of forging include bolts, disks, gears, turbine disk, crank shaft, connecting rod, valve bodies, small components for hydraulic circuits etc.

Forging has several advantages. Closer dimensional accuracies achieved require very little machining after forging. Material saving is the result. Higher strength, greater productivity, favorable grain orientation, high degree of surface finish are other merits. However, complex die making is costly.

1.3 Types of forging:

In forging the material is deformed applying either impact load or gradual load. Based on the type of loading, forging is classified as hammer forging or press forging. Hammer forging involves impact load, while press forging involves gradual loads.

Based on the nature of material flow and constraint on flow by the die/punch, forging is classified as open die forging, impression die forging and flashless forging.

Open die forging: In this, the work piece is compressed between two platens. There is no constraint to material flow in lateral direction. Upsetting is an open die forging in which the billet is subjected to lateral flow by the flat die and punch. Due to friction the material flow across the thickness is non uniform. Material adjacent to the die gets restrained from flowing, whereas, the material at center flows freely. This causes a phenomenon called barreling in upset forging.

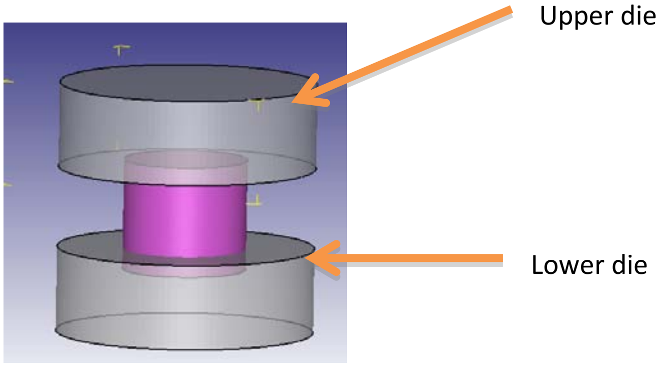

Fig. 1.3.1: Axisymmetric Upset Forging

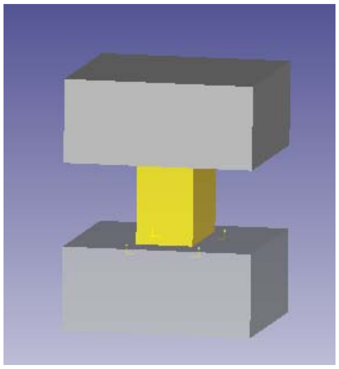

Fig. 1.3.2: Plane strain forging

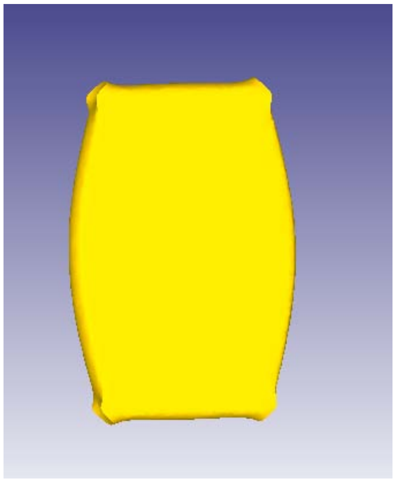

Fig. 1.3.3: A forged rectangular billet exhibiting bulging

Impression die forging both die and punch have impressions, shapes which are imparted onto the work piece. There is more constrained flow in this process. Moreover, the excess metal flows out of the cavity, forming flash.

Flashless forging – in this the work piece is totally constrained to move within die cavity. No excess material and hence no flash forms. Flashless forging involves high level of accuracy. Design of shape of die cavity, finished product volume are important.

1.4 Open die forging:

In open die forging a cylindrical billet is subjected to upsetting between a pair of flat dies or platens. Under frictionless homogeneous deformation, the height of the cylinder is reduced and its diameter is increased. Forging of shafts, disks, rings etc are performed using open die forging technique. Square cast ingots are converted into round shape by this process.

Open die forging is classified into three main types, namely, cogging, fullering and edging.

Fullering and Edging operations are done to reduce the cross section using convex shaped or concave shaped dies. Material gets distributed and hence gets elongated and reduction in thickness happens. Cogging operation involves sequence of compressions on cast ingots to reduce thickness and lengthen them into blooms or billets. Flat or contoured dies are used.

Swaging is carried out using a pair of concave dies to obtain bars of smaller diameter.

1.5 Closed die forging:

It is also known as impression die forging. Impressions are made in a pair of dies. These impressions are transferred to the work piece during deformation. A small gap between the dies called flash gutter is provided so that the excess metal can flow into the gutter and form a flash. Flash has got a very important role during deformation of the work piece inside the die cavity. Due to high length to thickness ratio of the flash gutter, friction in the gap is very high. Due to this the material in the flash gap is subjected to high pressure. There is high resistance to flow. This in turn promotes effective filling of the die cavity. In hot forging, the flash cools faster as a result of it being smaller in size. This enhances the resistance of the flash material to deformation resistance. As a result of this, the bulk of work piece is forced to deform and fill the die cavity more effectively – even intricate parts of the die cavity is filled.

Flash is subsequently trimmed off in order to obtain the required dimensions on the forged part. Often multiple steps are required in closed die forging.Flash is to be properly designed so that the metal could flow and fill the intricate parts of the die cavity. A thin flash with larger width requires higher forging loads. Before getting forged to intermediate shape inside the primary die set called blocking die, the billet is fullered and edged. This is called preforming. Subsequently, it is forged to final shape and dimensions in the finishing die. Closer dimensional accuracy is possible in closed die forging. However, higher forging loads are required. Parts with wider and thinner ribs, or webs are difficult to forge as they require higher forming loads. Impression dies are usually provided with taper called draft of 5° in order to facilitate easy removal of the finished part. Die preheating may be required to prevent the die chilling effect which may increase the flow stress on the periphery of the billet. As a result, incomplete filling or cracking of the preform may occur.

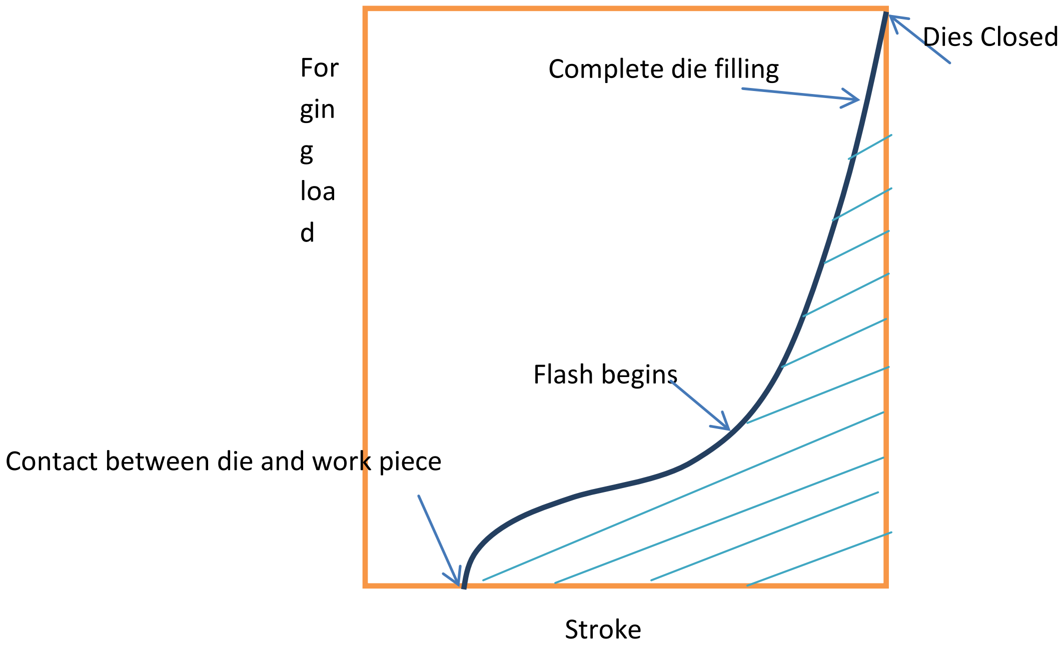

Fig. 1.5.1: Load-stroke diagram for closed die forging

Dimensional tolerances in impression die forging may be as close as ±0.5% of the dimensions of the forged part. In case of hot forging, dimensional accuracy is less.

Some of the factors such as die surface finish, draft allowance, accuracy of die impression dimensions, die wear, lubrication etc control the quality of finished product.

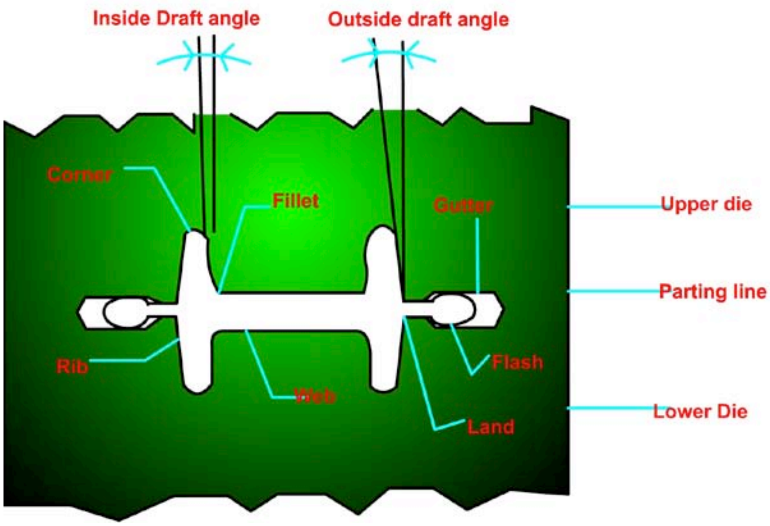

Fig.1.5.2: Parameters of impression die forging

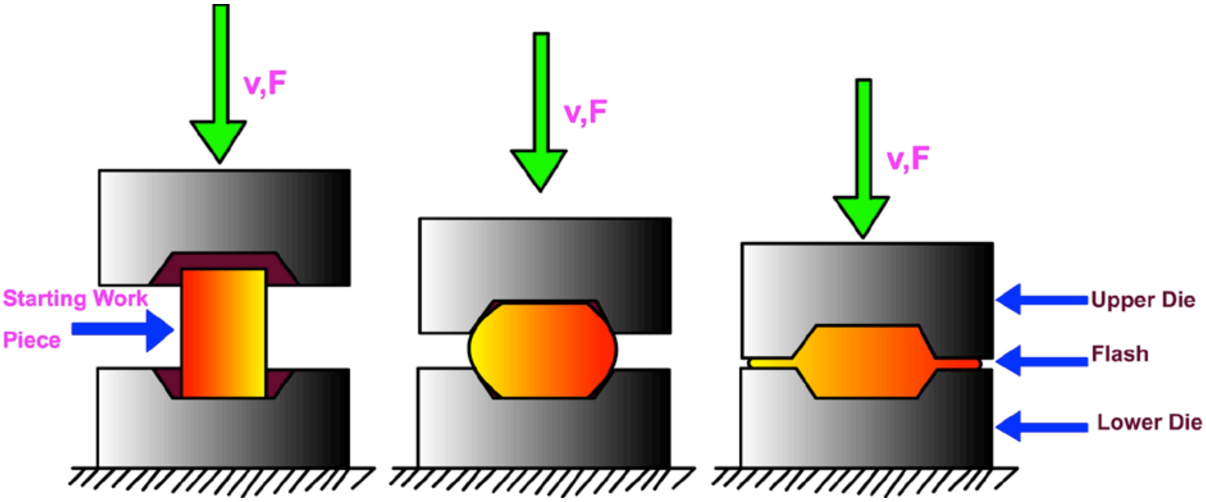

Fig.1.5.3: Stages of closed die forging process

1.5.1 Forging load for impression die forging:

Predicting the forging load for impression die forging is rather empirical due to the complexities of material flow involved.

One empirical relation for forging load, given by Schey is as followed:

$F = C_1 Y_f A_f$, where $C_1$is a shape factor or constraint factor which depends on the complexity of the forging process. $Y_f$is the flow stress of material at the given strain,A_f is the projected area of the forging.

<u>Typical values of C_1:</u>

Simple upsetting	1.25 to 2.5
Flashless forging (Coining)	5 to 8
Complex forging with flash	8 to 12

From the above equation, one can determine the capacity of forging press, as the force predicted by the empirical equation is the highest.

1.6 Precision die forging:

Near-net-shape forming is possible through precision die forging, in which high dimensional accuracy, elimination of after-machining and complex shapes of parts are achieved through precision dies and higher forging loads are achieved.

Alloys of aluminium, titanium, magnesium are commonly precision forged. Ferrous materials are difficult to precision-forge because of die wear, higher temperatures of forging, excessive forging loads requirement.

1.7 Flashless forging

It is a closed die forging process in which the work volume is equal to die cavity volume, with no allowance for flash. Excess material or inadequate material will lead to defective part. If billet size is less then underfilling takes place. Over sized billet leads to die damage or damage to the press.

A variant of closed die forging is **isothermal forging**. In this process, the die is heated up to the same temperature of the billet. This helps in avoiding die chilling effect on work piece and lowering of flow stress. This process is suitable for complex parts to be mass-produced.

Coiningis a special type of closed die forging. Complex impressions are imparted to both surfaces of the blank from the die. Forging loads involved are very high – as high as 6 times the normal loads. Minting of coins is an example of this process.

Coining, when used for improving surface finish of products is called sizing.

Piercing: It is a process in which a punch makes deep indentations to produce cavity on workpiece. Work piece may be kept inside a die or may be free. Higher forming loads are required.

Heading: Heads of bolts, nails are made by heading, which is an upsetting process. Special types of machines are used for heading.

1.8 Roll forging:

In this process, the bar stock is reduced in cross-section or undergoes change in cross-section when it is passed through a pair of grooved rolls made of die steel. This process serves as the initial processing step for forging of parts such as connecting rod, crank shaft etc. Finished products like tapered shafts, leaf springs can also be made.

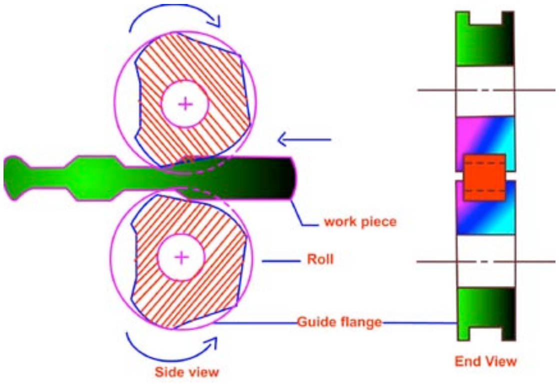

Fig.1.8.1: Roll forging

A particular type of roll forging called **skew rolling** is used for making spherical balls for ball bearings. In this process, the cylindrical bar stock is fed through the gap between a pair of grooved rollers which are rotating. Continuous rotation of the rolls and the stock gives raise to formation of a spherical shaped blank, which is subsequently finished to required dimensions.

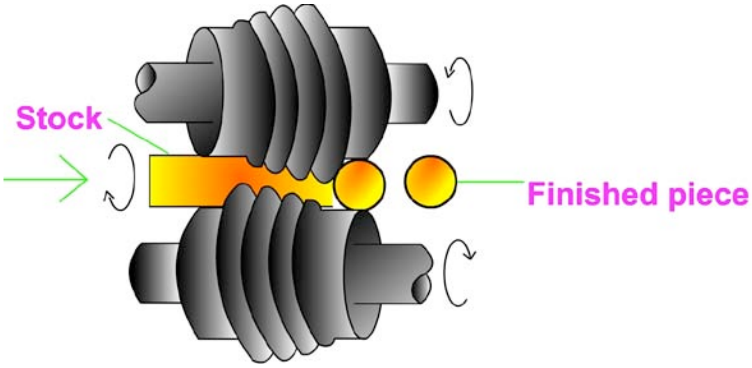

Fig. 1.8.2: Skew rolling process

1.9 Rotary forging:

In this process the punch is given orbital rocking motion while pressing the workpiece. As a result of this the area of contact between work and punch is reduced. Therefore lower forging loads are sufficient. The final part is formed in several smaller steps. Example of parts produced by this process include bevel gears, wheels, bearing rings.

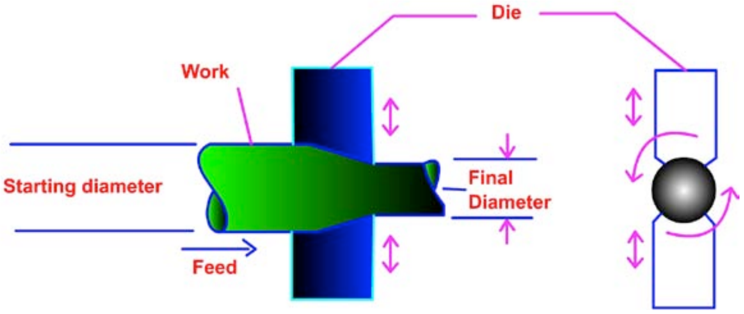

Fig. 1.9: Swaging

Hubbing: It is a pressing operation in which a hardened steel block, with one end machined to the form, is pressed against a soft metal. This process is used for making mold cavities. Hardened steel form is called hub. Hubbing is advantageous because it is easy for machining the positive form than machining the negative cavity.

Forging Equipment and General analysis of forging

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1.Forging Equipment and General analysis of forging

1.1 Forging equipment

Forging presses apply the required force gradually. Presses are of hydraulic type, mechanical or screw type. Eccentrics, knuckles or cranks are used in these presses for converting rotary motion into linear motion of the ram. The stroke of ram decides the energy available at the end of stroke. Hydraulic presses use hydraulic power. They are power driven machines. They are usually slow in operation. Screw presses operate based on friction wheel and screw. Both presses operate at slower ram speeds and can provide constant ram force. Presses give a squeezing type of action on the workpiece. They are suitable for forging and long stroke operations. Hydraulic presses are suitable for extrusion type operations as full load is available at all times. In power hammers, the total energy available for forging is equal to the kinetic energy of the ram plus the hydraulic pressure energy. In case of flywheel operated presses, the energy available is dependent on the moment of inertia of flywheel as well as its rotational speed.

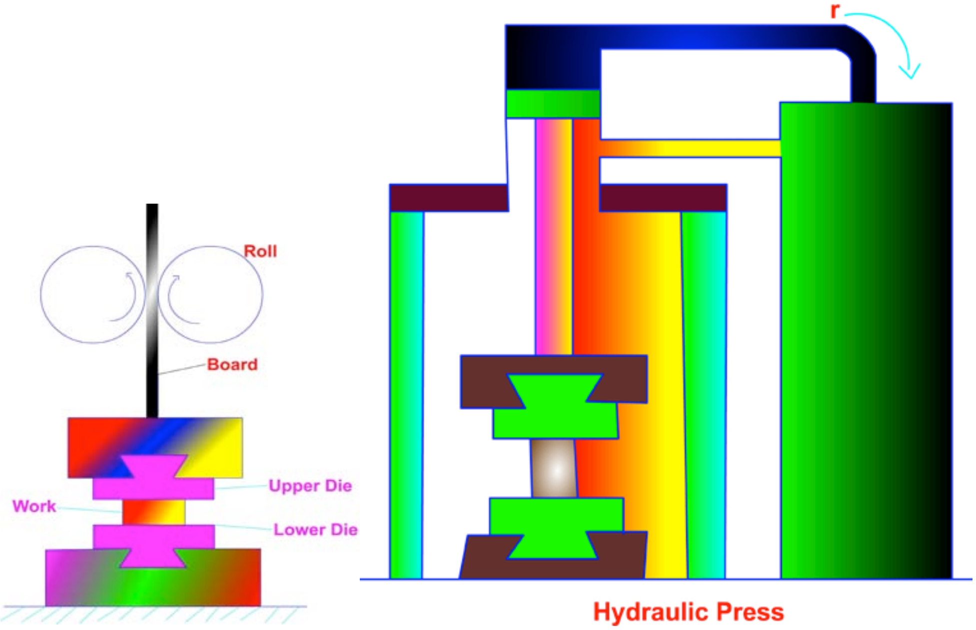

Fig. 1.1.1: A board hammer and hydraulic press

Forging hammers provide impact loads. Gravity hammers provide the forging load by the falling weight of the ram. One half of the die is fixed on the ram and the other half is fixed on machine table. They are suitable for impression die forging, where a single blow or a few blows will deform the metal inside the cavity. Board hammers operate by frictional rising of the board with ram. Power hammers use pneumatic or steam power additionally to accelerate the ram. Total energy available at ram end is the sum of kinetic energy of the ram and the power of the air or steam used.

1.2 Analysis of forging:

A number of methods are available for the analysis of metal forming processes. Slab method is based on mechanics approach, in which we consider the static equilibrium of forces on the billet. In another method, the velocity field of the deforming material is found first. From kinematically admissible velocity field, the work done during the process is formulated. The formulated work equation is then solved. This approach is known as upper bound analysis.

In this section we analyse the open die forging processes – upsetting of plane strip and circular disc in order to determine the forging force, using slab method. First we ignore friction and write down the theoretical equation for the forging load. Then we consider the effect of friction.

1.2.1 Homogeneous upsetting:

Considering a cylindrical billet of initial height h_o, the strain rate in upset forging can be expressed as: $\dot{\varepsilon} = -v/h$ where h is the instantaneous height and v is the velocity of the ram. As the height of the billet gets reduced the strain rate increases to very high values.

The true height strain of the billet can be found from the formula:

$$\varepsilon = ln\frac{h_o}{h_f} \qquad \text{-------------------} \ 1$$

where h_o is initial height and h_f is final deformed height of billet.

Neglecting friction at interface between the billet and die, the ideal forging force at the die-work interface is given by:

$F = Y A,$ -------------------- 2

A is area of billet at any instant. Y is yield stress of the material of billet.

Applying volume constancy principle we have:

$A h = A_o h_o$

Therefore, $F = Y\ A_o h_o / h$ --------------------- 3

Here, Y can be taken to be the flow stress of the material at a given strain.

Work done during the deformation is given as:

W = = $A_o h_o \int_0^{\varepsilon} \sigma d\varepsilon$------------------------------- 4

The average flow stress $\bar{Y}$ is given by: $\bar{Y} = \frac{k\varepsilon^n}{n+1}$ -------------- 5

Therefore, work done is given by **$W = \bar{Y}\varepsilon$Volume $= \bar{Y}\varepsilon A_o h_o$**-----------6

And the forging load is **$F = \bar{Y}$** A -----------------7

The area of the forged disc keeps increasing as forging proceeds. As a result the force required increases.

Flow stress also increases due to work hardening. This also leads to the application of greater forging load with continued deformation.

Frictionat work-tool interface makes the flow of metal nonhomogeneous. Metal in contact with the die surface is subjected to maximum restraint due to friction shear stress. Flow here is the least. Whereas, at the central section the restraint being the lowest, material flow is the maximum here. This kind of non-uniform flow results in bulging of the lateral surface of the disc. This is called barreling. In case of rectangular billets, there will be double barreling.

In case of hot forging, the material in contact with the dies gets cooler and hence offers more resistance to deformation. The central section is offering least resistance to flow. Further, the coefficient of friction in hot forming is high. All these result in barreling.

Due to barreling, the forging load required is higher than that predicted by the theoretical equation above.

We can write the forging force for non-homogeneous upsetting as:

F = **$\bar{Y} A k_f$,** ---------------------------------**8**

wherek_f is a forging shape factor, given by:

$k_f = 1 + \frac{0.4\mu D}{h}$

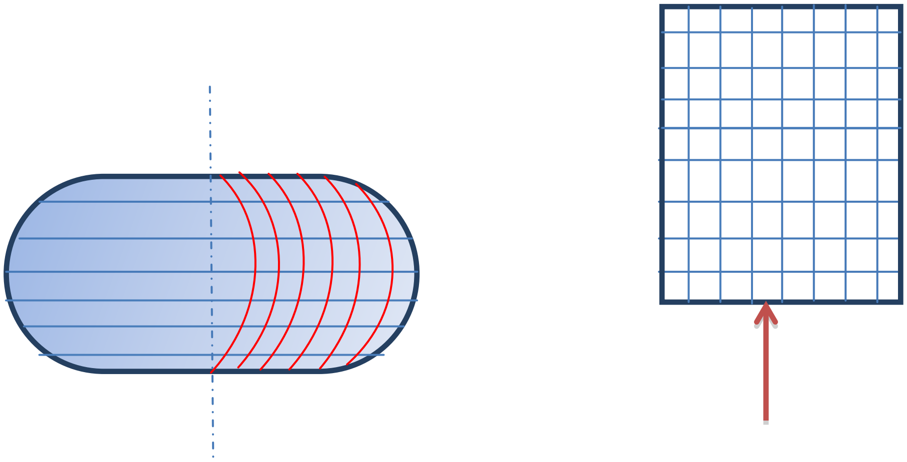

Fig. 1.2.1.1: Barreling during upset forging due to friction

Example: Cold upset forging of a cylindrical billet of initial height 60 mm and initial diameter 30 mm, results in a final reduced height of 40 mm. The material of the billet has flow stress given by the expression: $Y = 300\varepsilon^{0.2}$ MPa. The coefficient of friction between the billet and die surfaces can be assumed to be 0.1. What is the forging force required at the reduced height?

Solution:

We may use the approximate expression, equation 8, for solving this problem.

F = $\boldsymbol{\bar{Y}}$**A**$\mathbf{k_f}$

F is forging force, $\boldsymbol{\bar{Y}}$is average flow stress, A is area of billet.

Kf is a factor which accounts for friction and is given by:

$k_f = 1 + \frac{0.4\mu D}{h}$

Applying the principle of volume constancy,

Aoho = Afhf→Af= Aoho/hf→df = 51.97 mm

True strain = ln(ho/hf) = 0.405

Average flow stress = $\frac{k\varepsilon^n}{n+1}$ = 208.65 MPa

Kf = 1.052

F = 275.68 kN   Answer

Analysis of plane strain upset forging of rectangular billet

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1.1 Upsetting of rectangular plate-analysis **...3**

1.Analysis of plane strain upset forging of rectangular billet

There are different methods of analysis of bulk deformation processing, like slab analysis, slip line field line, upper bound analysis, FEM analysis. The outcome of all these analyses is the forming load.

In this section we focus on slab method, which is the simplest type of analysis for forming load.

1.1 Upsetting of rectangular plate-analysis

Consider a rectangular billet of height h_o, width (x axis) 2a and unit depth (z axis). Let this billet be subjected to plane strain upsetting. Plane strain condition here means there is no normal and shear strain along the z direction – depth direction. The slab undergoes strain only along the y axis-height direction and along the x direction – width direction.

We can make a force balance on a small elemental strip of width dx, height h and unit depth, as shown.

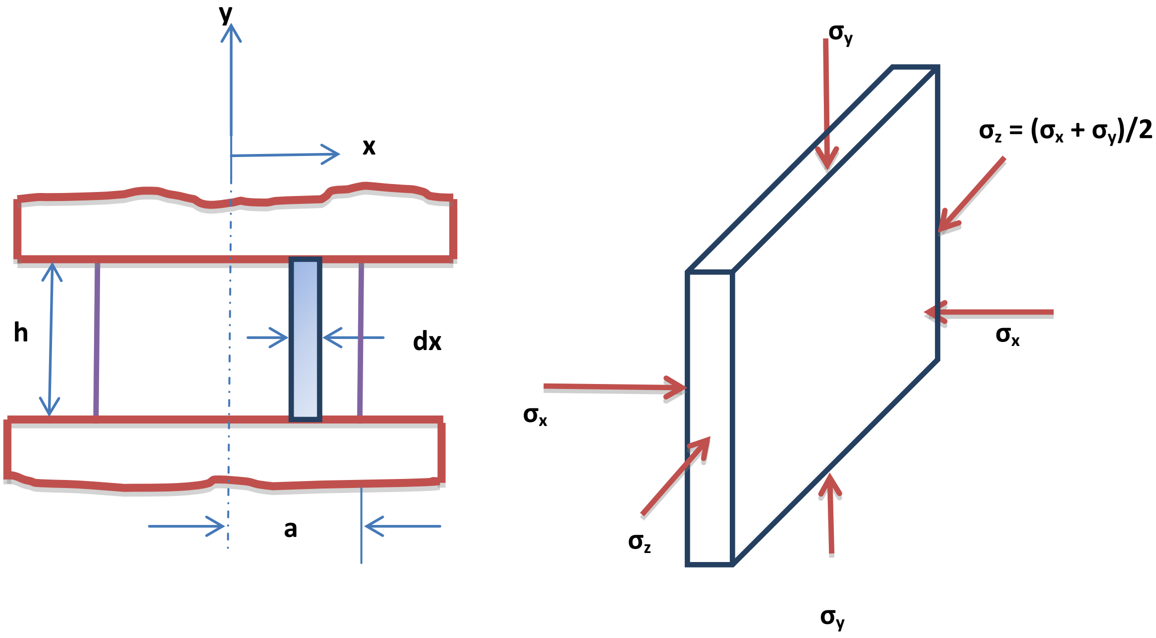

Fig. 3.1.1: Plane strain upsetting of rectangular billet and the stresses acting on the element of thickness dx

Assume that the lateral stress **σ_x**is uniform along the height of the element.

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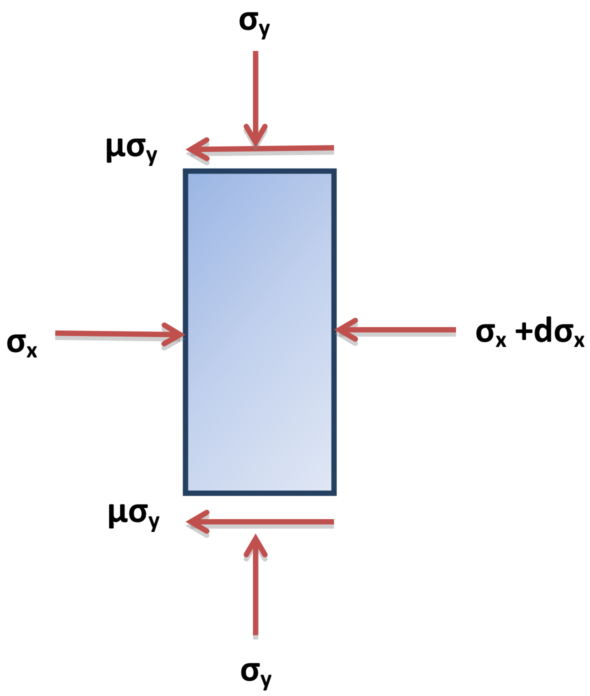

Fig. 3.1.2: Stresses acting on a small elemental billet of thickness dx and unit depth

Assumptions:

compressive stresses are positive.

Sliding Columbic friction

Coefficient of friction is low

The height of the billet is small so that the forging pressure is constant over the height of the billet.

Assume that σ_x and σ_y are principal stresses [Though σ_y can not be assumed as principal stress as a shear stress is also acting on the plane on which the normal stress is acting]

Here $\sigma_y$is the forging stress necessary at any height h of the billet.

Force balance on the element gives:

Assuming the dimension of the billet perpendicular to the plane of the paper,

$(\sigma_x + d\sigma_x)h + 2\mu\sigma_y dx - \sigma_x h = 0$ -----------------9

We have to eliminate σ_x because there are two unknowns in the above equation.

For eliminating σ_x we can apply the von Mises yield criterion for plane strain.

According to this criterion, we have:

$\sigma_y - \sigma_x = \frac{2}{\sqrt{3}}Y = Y'$ --------------------10

From this we have $d\sigma_y = d\sigma_x$

The force balance equation now becomes:

$\frac{d\sigma_y}{\sigma_y} = -\frac{2\mu}{h}dx$ ------------------------------11

Upon integration, we get:

σ_y = A$e^{-\frac{2\mu x}{h}}$ ----------------------------------12

To solve the constant A, we need a boundary condition.

At x = a, σ_x = 0 [free surface]

From the yield criterion we have: At x=a, $\sigma_y = Y'$

Substituting this in equation 12 and simplifying we get,

$p = \sigma_y = Y'[e^{\frac{2\mu(a-x)}{h}}]$ -----------------------13

P is the forging pressure

Equation 13 can also be written as:

P = Y'[$e^{\frac{L\mu(1-\frac{2x}{L})}{h}}$] --------------------14

Where L = 2a → width of the billet

From the above equation we find that as L/h increases, the forging pressure increases – resistance to compressive deformation increases. This fact is utilized in closed die forging where the deformation resistance of flash, being high [due to high L/h] the die filling is effective.

Note: Y' is plane strain yield strength of the material

If the material is work hardening type of material, we have to replace Y' with Y'_f which is the flow stress of the material

The variation of forging pressure normalized with plane strain yield strength Y' is shown with respect to the billet thickness:

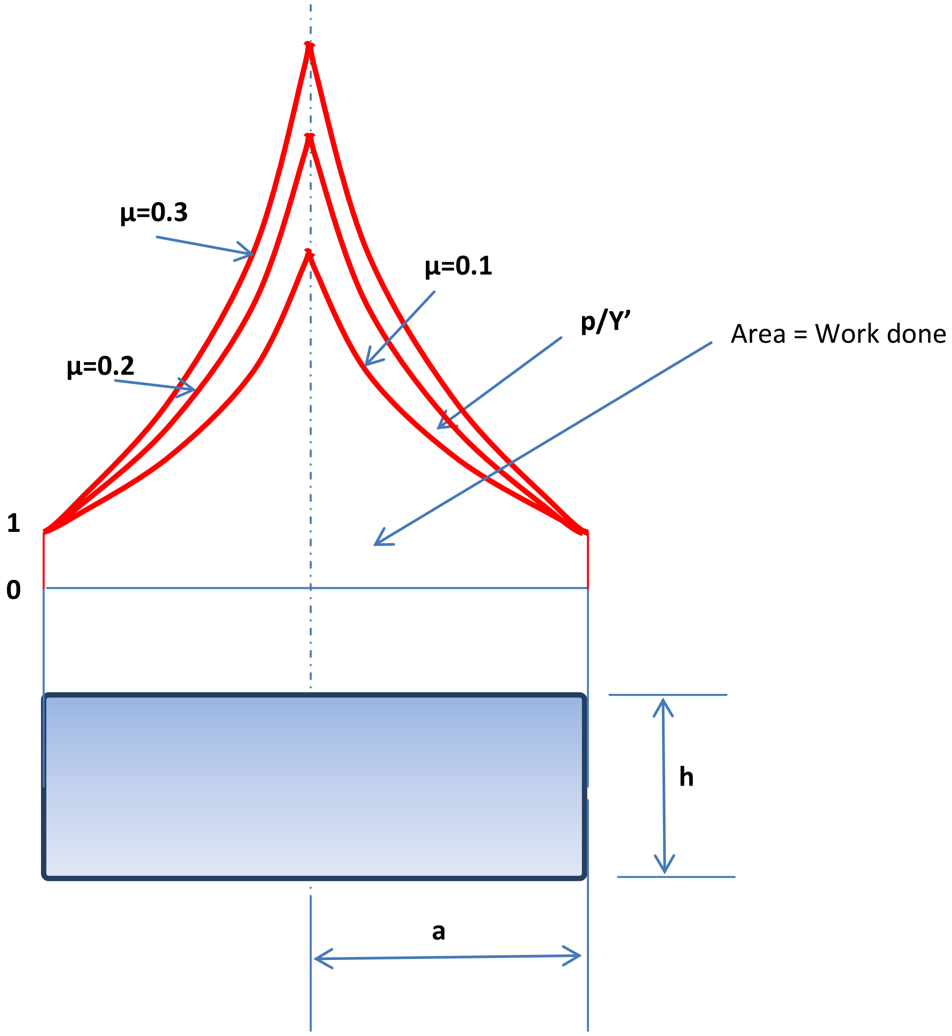

Fig. 3.1.3: Friction hill in plane strain upsetting under sliding friction

Forging pressure variation across the billet due to friction is shown above. The pressure distribution curve is called friction hill. Area under the friction hill represents the forging work done.

As shown in figure, as the coefficient of friction increases, the forging pressure increases and hence the work done.

Average forging pressure:

The average forging pressure is given as:

$$\bar{p} = \frac{1}{a}\int_0^a p dx \quad \text{------------}15$$

Substituting for p from equation 13, we get:

$$\bar{p} = \frac{\bar{Y}}{\frac{2\mu a}{h}}(e^{\frac{2\mu a}{h}} - 1)$$

We can get approximate expression for average forging load by expanding exponential function as infinite series. We get:

$$\bar{p} = Y'(1 + \frac{\mu a}{h}) \quad \text{----------------}16$$

Note that the forge pressure is a function of instantaneous height of billet. As height gets reduced, after successive plastic flow, forging pressure increases.

If the rectangular billet is subjected to plane stress compression – stress acting along the height axis and the length axis, there will be material flow in the width direction. It is found that the extent of flow along width direction is several times greater than the flow along longitudinal direction. Because of lower friction along width, material flows freely along width direction.

If a rectangular block is compressed, due to friction and non-uniform flow, bulging and barreling take place. Bulging refers to the non-uniform flow considered on the plane of the loading, while barreling refers to the non-uniform deformation along the height of the specimen. The reason for bulging and barreling is the material flow along the diagonal direction is rather sluggish, compared to the other directions.

Sticking friction:

The frictional shear stress – µp increases towards the axis as the forging pressure p increases.

However, the maximum frictional shear stress can not exceed the shear yield strength of the material. When the limiting condition of τ = k, we can say sticking exists at the interface.

Generally, we can relate the friction shear stress with shear yield strength by the relation:

$\tau = mk$

m is friction factor, which can not exceed 1.

Under sticking friction the friction shear stress and shear yield strength are related as:

$\tau = k$ -------------------------17

where k is shear yield strength. For sticking friction, the limit of friction shear stress is the shear yield strength of the material → m=1.

In general, with $\tau = mk$, the forging pressure is given by:

$P = Y'\frac{m}{h}(a-x) + Y'$ ---------------------------------18

As per the above equation, with sticking friction [m = 1], one can write the forging pressure as:

$P = Y'\frac{(a-x)}{h} + Y'$ -----------------------19

This is a linear relation, which is shown in figure below:

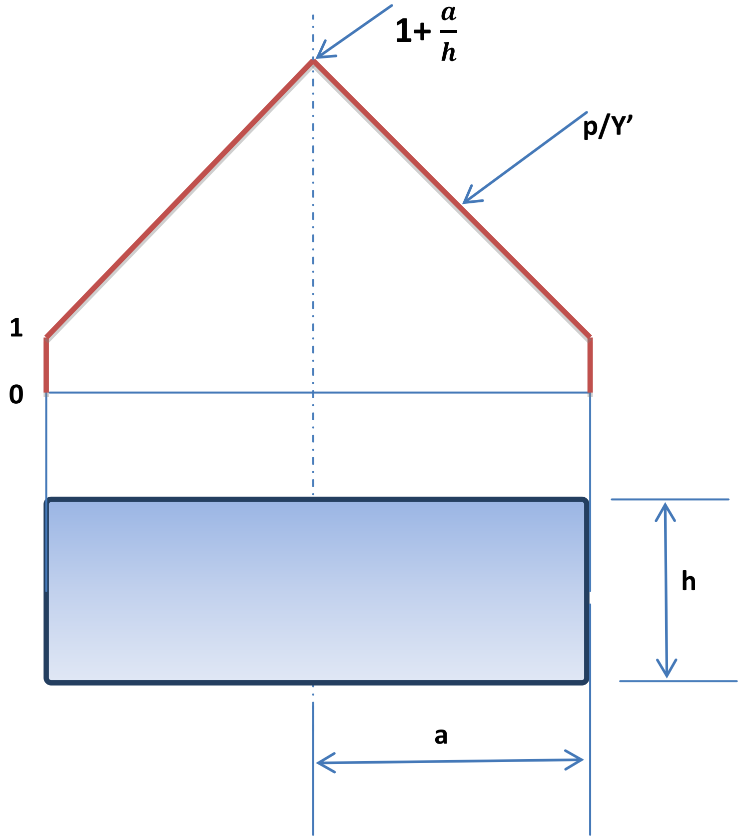

Fig. 3.1.4: Upset forging with sticking friction – variation of forging pressure

Example: A rectangular block of height 40 mm, width 100 mm and depth 30 mm is subjected to upset forging under sliding friction condition, with a friction coefficient of 0.2. The material of the billet has flow stress expressed as: $Y = 300\varepsilon^{0.2}$. Calculate the forging load required at the height reduction of 30%, assuming plane strain compression.

Solution: Due to plane strain assumption, the depth side of the block remains without deformation. We can use the solution obtained for plane strain compression. The average forging pressure is given by:

$$\bar{p} = \frac{\bar{Y}}{\frac{2\mu a}{h}}\left(e^{\frac{2\mu a}{h}} - 1\right)$$

Given: a_o = 50 mm, h_o = 40 mm, h_f = (1-0.3)h_o = 28 mm, depth = w = 30 mm.

To find width after the deformation, we can use volume constancy.

$2a_oh_o = 2ah$ → a = 71.43 mm

True strain = $\ln(h_o/h_f)$ = 0.357

Average flow stress = $\frac{k\varepsilon^n}{n+1}$= 203.4 MPa

Average forging pressure = 199.41X1.773 = 353.59 MPa.

Average Forging load = 353.59 X 71.43 X 30 = 757. 7 kN(For one half of the bar)

Total forging load = 2X757.7kN.

Analysis of Axi-symmetric forging of a disk

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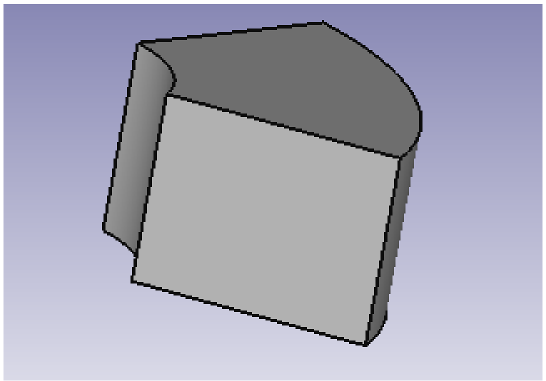
1.1 Axi-symmetric forging of a disc-analysis: 3

1. Analysis of Axi-symmetric forging of a disk

1.1 Axi-symmetric forging of a disc-analysis:

Consider a solid circular disk of diameter R and height ho. This disc is subjected to axial upsetting between two dies. The objective is to determine the forging pressure required at any height h of the disk. We have to consider sliding friction at interface, with coefficient of friction taken to be μ.

We also assume that the axial compressive pressure p is constant over the thickness of the disk – because the disk has lower height.



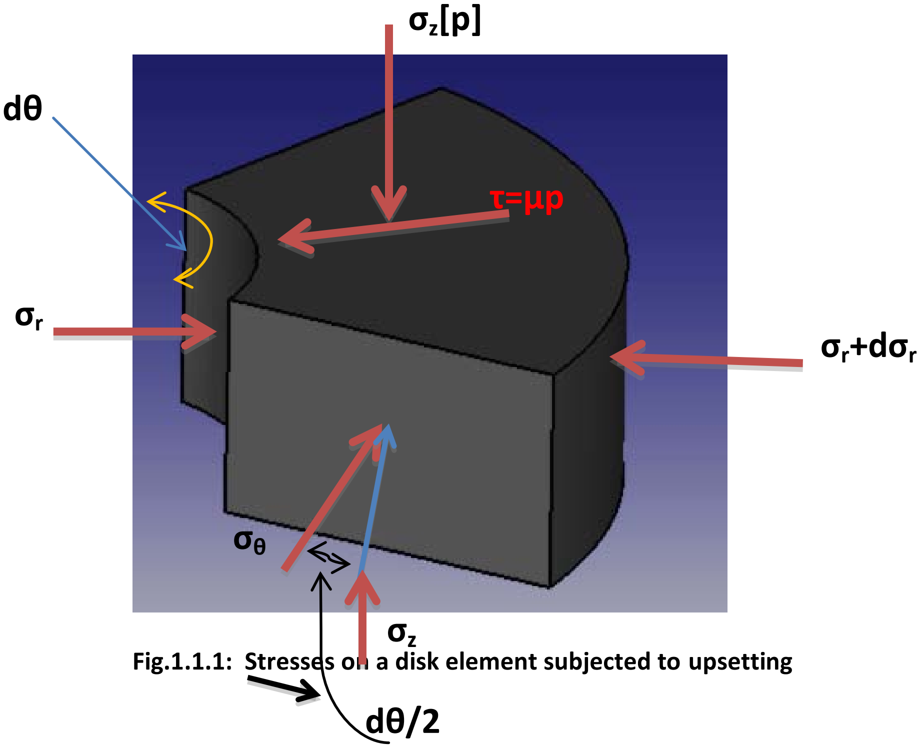


Fig.1.1.1: Stresses on a disk element subjected to upsetting

Consider the disk element as shown above, with height h, radius r and radial thickness dr, angle $d\theta$.

The various stresses acting on the element are shown in figure.

Note that for axial symmetry, we have radial strain = circumferential strain→$d\varepsilon_r = d\varepsilon_x$.

Therefore, we have

$\sigma_r = \sigma_\theta$----------------------------20

Surface shear on top and bottom faces is opposing the radial flow of material. This is shown in figure above.

Due to frictional shear stress, lateral pressure is induced on the material.

We assume that $\sin d\theta/2 = d\theta/2$, because angle $d\theta$ is small.

Equilibrium of forces on the element after applying the approximation said above and the equality of radial and circumferential stresses (equation 20), gives:

$\frac{d\sigma_r}{dr} = -\frac{2\mu p}{h}$----------------------21

Now σ_r has to be eliminated.

We can apply the von Mises yield criterion for the compression. Assuming that all the three stresses are principal stresses, we find that:

$Y = p - \sigma_r$----------------------------22

Hence, $d\sigma_r = dp$--------------------23

Applying eqn 23 in eqn 21, we have

$\frac{dp}{p} = -\frac{2\mu dr}{h}$---------------------------24

Equation 24 can now be integrated, Integrating and applying the boundary condition:

at $r=R$, $\sigma_r = 0$

we obtain the final solution of equation 24 as:

$p = Ye^{\frac{2\mu(R-r)}{h}}$----------------- 25

For frictionless compression ($\mu=0$) we get p = Y.

With various coefficients of friction, the variation of forging pressure along the radial direction is shown in figure below:

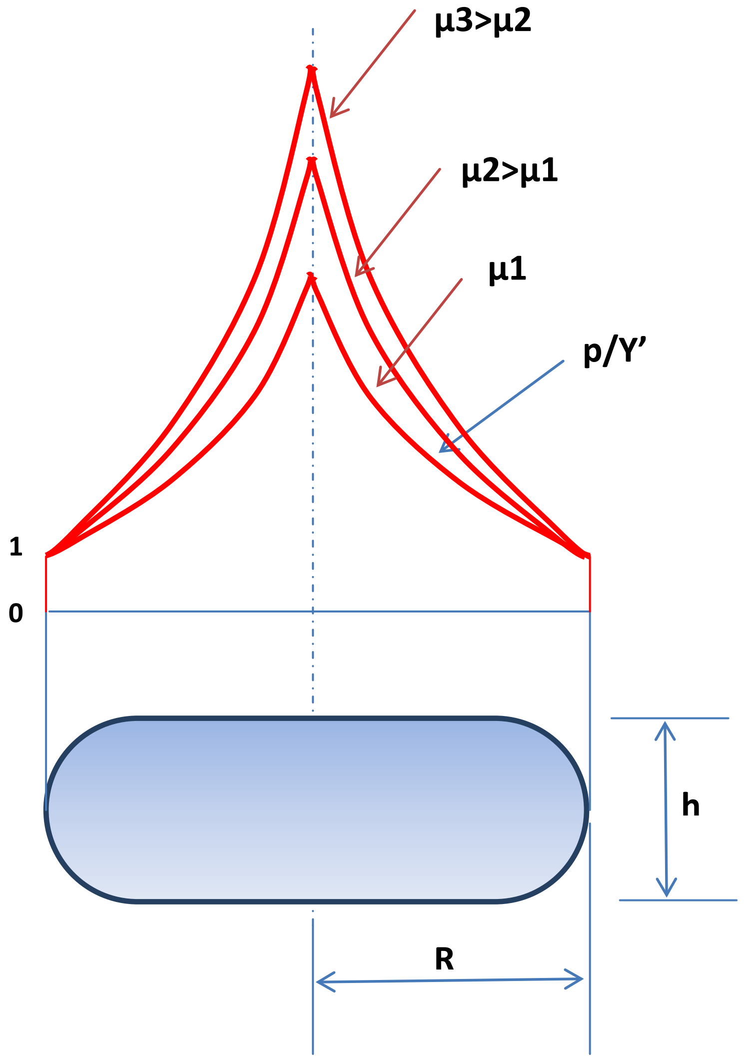


Fig. 1.1.2: Friction hill for sliding friction

The average forging pressure can be determined from the following integration:

$$P_{av.} = \frac{1}{\pi R^2}\int_0^R p2\pi r dr \text{ -----------------26}$$

$$= \frac{1}{2}\left(\frac{h}{\mu R}\right)^2 Y\left[e^{\frac{2\mu R}{h}} - \frac{2\mu R}{h} - 1\right]$$

Approximately,

The average pressure can be obtained as:

$\bar{p}$= Y(1+$\frac{2\mu R}{3h}$)--------------------27

For materials which undergo strain hardening, Y is replaced by the corresponding flow stress .

Coefficient of friction values for various forming operations are given in table:

Table 4.1.1: Coefficient of friction values for various forming operations

Process	µ - Cold forming	µ - Hot forming
Forging	0.05 to 0.1	0.2 to 0.7
Rolling	0.05 to 0.1	0.1 to 0.2
Drawing	0.03 to 0.1	0.1 to 0.2
Sheet metal working	0.05 to 0.1	

As the coefficient of friction increases, the forming pressure also increases.

The aspect ratio of the billet also has notable effect on the forging pressure.

Aspect ratio = diameter / height or = width / height

Effect of friction and aspect ratio on forging pressure is shown in figure below

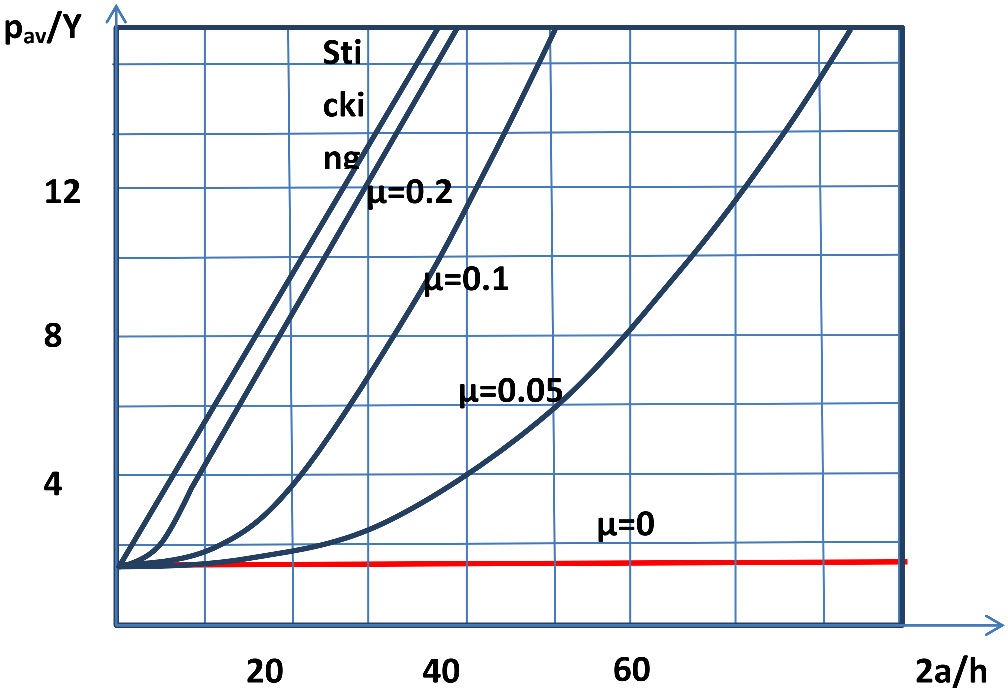


Fig. 1.1.3: Variation of forging pressure with aspect ratio of billet and coefficient of friction

Sticking friction:

Taking τ =k

We can get the forging pressure p as:

$$\frac{p}{k} = 1 + \frac{(R-r)}{h} \text{------------------------}28$$

If combination of sliding and sticking friction occurs, the distance from the axis where the sticking friction changes to sliding friction can be determined as followed:

At the location where the change occurs, namely, r, we can equate the shear stress due to sliding friction to that due to sticking friction:

τ = μp = K   (assuming m=1)

Substituting for p from eqn. 25, we can solve for r:

$$r = R - \frac{h}{2\mu} \ln\left(\frac{\mu k}{Y}\right) \text{----------------}29$$

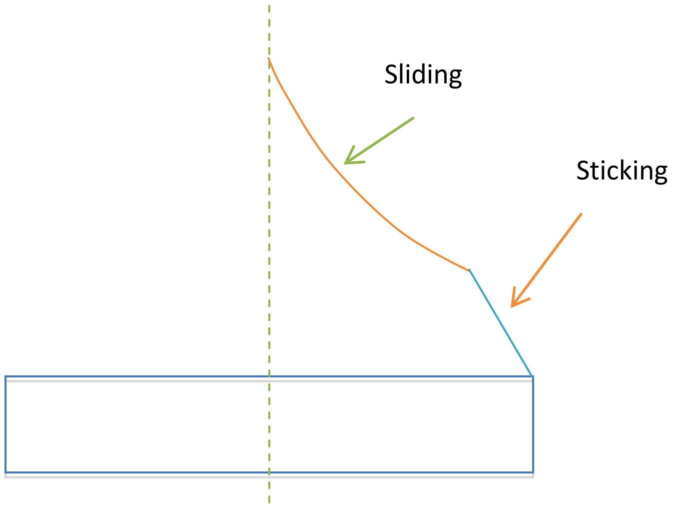


Fig. 1.1.4: Combined sliding and sticking friction

Example: A 40 mm diameter disk of initial height of 40 mm is upset forged between a pair of platens. The coefficient of friction at the interfaces is found to be 0.22. The material of the billet has a strength coefficient of 650 MPa and a strain hardening exponent of 0.16. What is the instantaneous forging force just at the point of yielding (assuming yield point strain = 0.002)? Determine the average force at the height reduction of 30%.

Solution:

Given disk with do = 40 mm, ho = 40 mm, μ=0.22, k=650 MPa, n=0.16.

To determine: a] the forging load at the commencement of yielding and b] average force at height reduction of 30%

We can use the expression for forging pressure for axisymmetric forging for solving this problem.

The average forge pressure is given by:

$$\bar{p}= Y(1+\frac{2\mu R}{3h})$$

a] At yielding

$$\varepsilon = 0.002$$

Y = 240.48 MPa

$$\varepsilon = \ln\left(\frac{ho}{hf}\right)$$

Therefore hf = 39.92 mm

Rf = 20.02 mm

Average pressure = **258.17** MPa

b] At 30% height reduction:

hf = (1-0.3)ho = 28 mm

Rf = 23.9 mm

Strain = 0.358

Y = 551.41 MPa

Average pressure = 620.44 MPa

Average forging force = 620.44 X Final Area = 1.11 MN

Forging die design and Forging defects

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1. Forging die design and Forging defects

1.1 Forging die-design aspects:

Die design is more empirical and requires experience. Design of die depends on the processing steps, nature of work piece material, its flow stress, temperature of working, frictional condition at interface etc.

Volume of billet is to be accurately calculated so that there is neither under filling nor excess filling.

Proper selection of parting line – the line where the two dies meet is very important. Parting line is so chosen that the flow of material is uniform ly divided between the two dies – as far as possible.

Maximum of 3% of the forging thickness is allowed for flash thickness. Flash gutter is to be provided in order to reduce forging loads.

Draft angles between 3^o and 10^o are normally provided for easy ejection of forging.

Corner radii are to be larger as far as possible to facilitate smooth flow of material.

Forging temperature decides the type of die material for forging.

Commonly, for ferrous alloys, a forging temperature of 900 to 1200^o C is used. For aluminium alloys, it is from 400 to 450^o C. For copper alloys, it is 625 to 950^o C.

Die materials commonly used are tool steels, high carbon high chromium die steels, high carbon, high chromium, molybdenum die steels etc.

Lubrication also plays a role in the accuracy and surface finish of forging. Commonly, for hot forging, glass, graphite, molybdenum disulfide are used as lubricants. For cold forging, mineral oils are used.

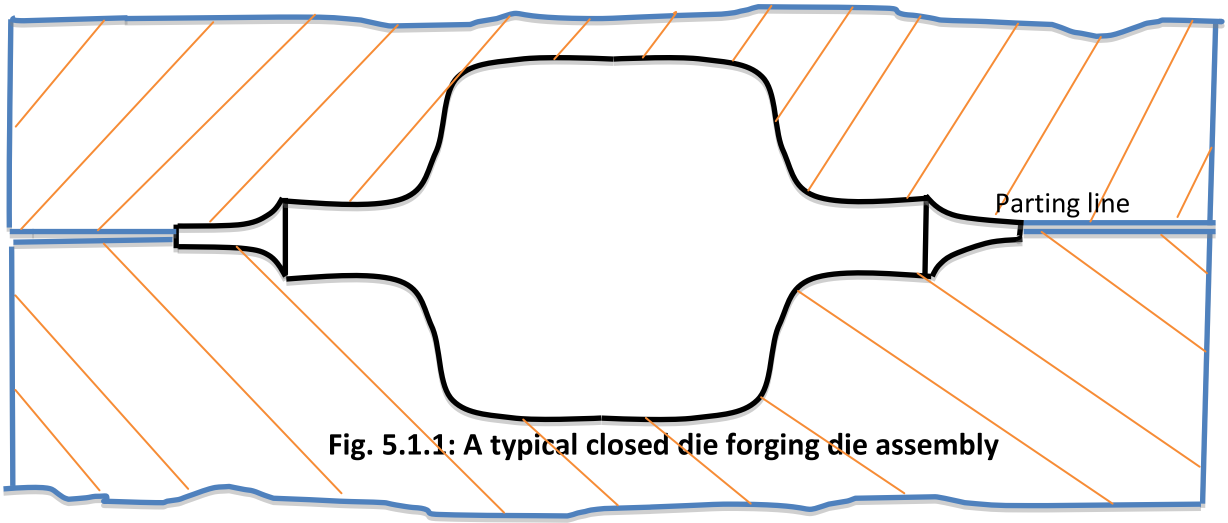


Fig. 5.1.1: A typical closed die forging die assembly

1.2 Forging defects:

One of the major defects in upset forging or open die forging is the surface cracks originating on the bulged or barreled surface due to excessive tensile hoop stress. Surface cracks may be longitudinal or inclined at 45^o angle. If the circumferential stress is tensile, longitudinal cracks occur. If hoop stress is compressive, 45^o cracks are originated.

Another problem come across in open die forging may be buckling if the height of the billet is high – if the h/D ratio exceeds 2.

In closed die forging if volume of material taken is excess or if the thickness of flash is too large, then the excess metal from flash recess may flow into the already forged part and lead to internal cracks.

In impression die forging, the radii of internal sections are to be designed properly. If corner radii are too small the material may fold against itself and produce cold shut. However, internal cracks are avoided due to compressive stress induced by die wall.

Another defect is due to grain flow lines in closed die forging. If grain flow lines reach the surface [end grains], grain boundaries are exposed to surface. Such exposed grain boundaries are easily attacked by corrosive media.

Cracks on the surface may also be caused due to die wall chilling, thereby increasing the resistance to flow on the surface. Surface cracks are also caused due to excess working as the surface gets cooled faster due to heat loss.

Forged parts have characteristic fibrous structure due to grain flow. This may result in anisotropic properties of forged parts. In order to avoid this problem, the maximum deformation is restricted to 60 to 70% area reduction.

Presence of residual stress in large forgings may lead to formation of internal cracks when such forgings are subjected to fast cooling after heat treatment. To avoid internal cracks, the cooling rate is reduced by keeping the hot forgings buried in sand.

Summary of forging defects:

<u>Coldforging:</u>

Dead metal zone/shear band

Centre burst

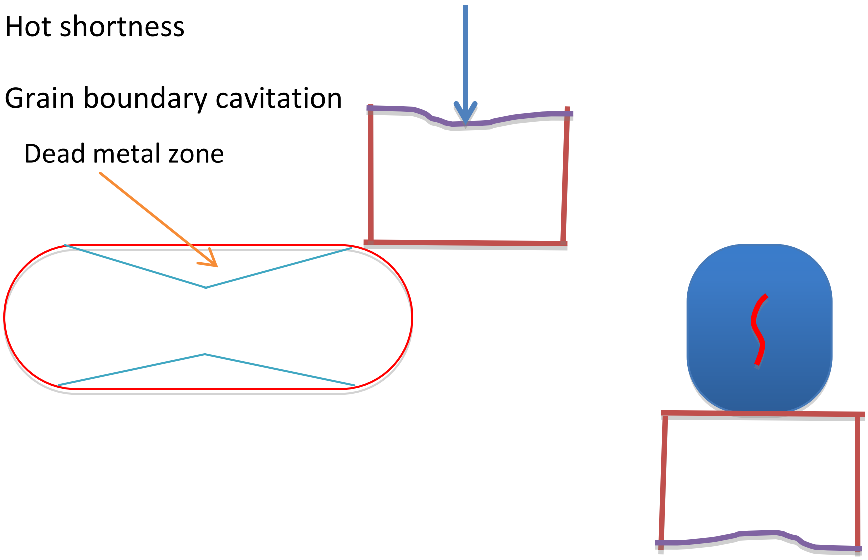
Surface crack

<u>Hot forging:</u>

Shear bands

Hot shortness

Grain boundary cavitation



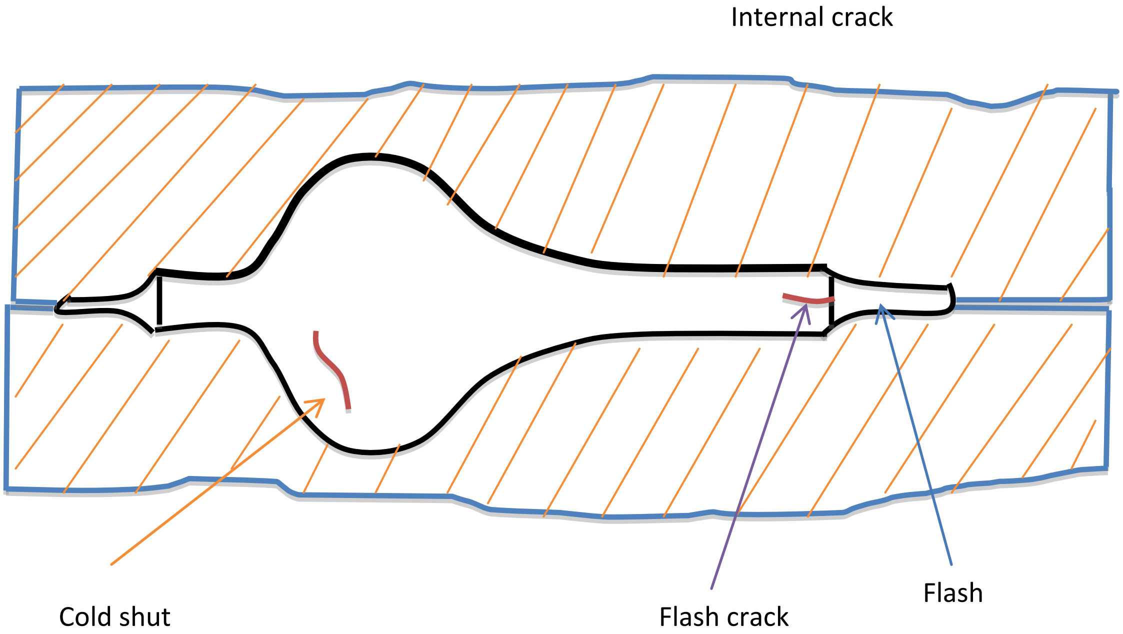


Fig. 1.2.1: Some forging defects

1.3 Introduction to powder forging

Powder metal technology is one of the most economic productions methods extensively used in modern industries. Near-net-shape manufacturing of small parts is one of its advantages. Due to inherent porosity in sintered metal, the compacted and sintered alloys have limited applications. To eliminate porosity, post-sintering processing such as forging, rolling etcare employed. Powder forging serves as a very essential, industrially important process, due to its advantages such as high strength, high fatigue limit. In powder forging, preforms are obtained through the blending, compaction and sintering route. The sintered compacts with porosity in the range of 12 to 8% are then subjected to closed die forging or upset forging or extrusion forging in order to obtain the finished product with very little subsequent machining.

Behaviour of porous sintered preforms is different from wrought metals. Porous preforms are compressible, therefore there is considerable volume reduction during forging. Yield criteria for porous preforms, therefore, include density as one of the parameters. Poisson's ratio for porous materials also is a function of density.

It is of the form: $\upsilon = 0.5(\frac{\rho}{\rho_t})^2$

The yield criterion for porous solids is given in the form as followed:

$$Y^2(\rho,\varepsilon) = [\frac{[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2]}{2} + (1-2\upsilon)[\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1]]$$

As seen from the equation above, the yielding of a porous material depends on density also.

Powder compaction using die set is shown in diagram below:

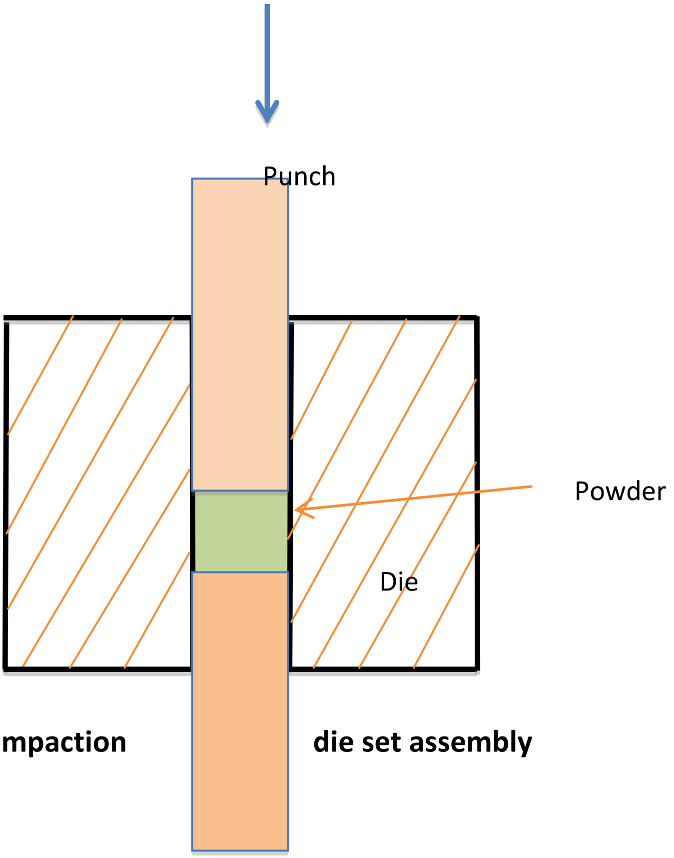


Fig. 1.3.1: Powder compaction die set assembly

Rolling - Introductory concepts

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1. Rolling - Introductory concepts:

1.1 Introduction

Rolling is one of the most important industrial metal forming operations. Hot Rolling is employed for breaking the ingots down into wrought products such as into blooms and billets, which are subsequently rolled to other products like plates, sheets etc.

Rolling is the plastic deformation of materials caused by compressive force applied through a set of rolls. The cross section of the work piece is reduced by the process. The material gets squeezed between a pair of rolls, as a result of which the thickness gets reduced and the length gets increased.

Mostly, rolling is done at high temperature, called hot rolling because of requirement of large deformations. Hot rolling results in residual stress-free product. However, scaling is a major problem, due to which dimensional accuracy is not maintained. Cold rolling of sheets, foils etc is gaining importance, due to high accuracy and lack of oxide scaling. Cold rolling also strengthens the product due to work hardening.

Steel ingot is the cast metal with porosity and blowholes. The ingot is soaked at the hot rolling temperature of 1200^oC and then rolled into blooms or billets or slabs.

Bloom is has a square cross section, with area more than 230 cm^2. A slab, also from ingot, has rectangular cross-section, with area of at least 100 cm^2 and width at least three times the thickness. A billet is rolled out of bloom, has at least 40 mm X 40 mm cross-section.

Blooms are used for rolling structural products such as I-sections, channels, rails etc. Billets are rolled into bars, rods. Bars and rods are raw materials for extrusion, drawing, forging, machining etc. Slabs are meant for rolling sheets, strips, plates etc.

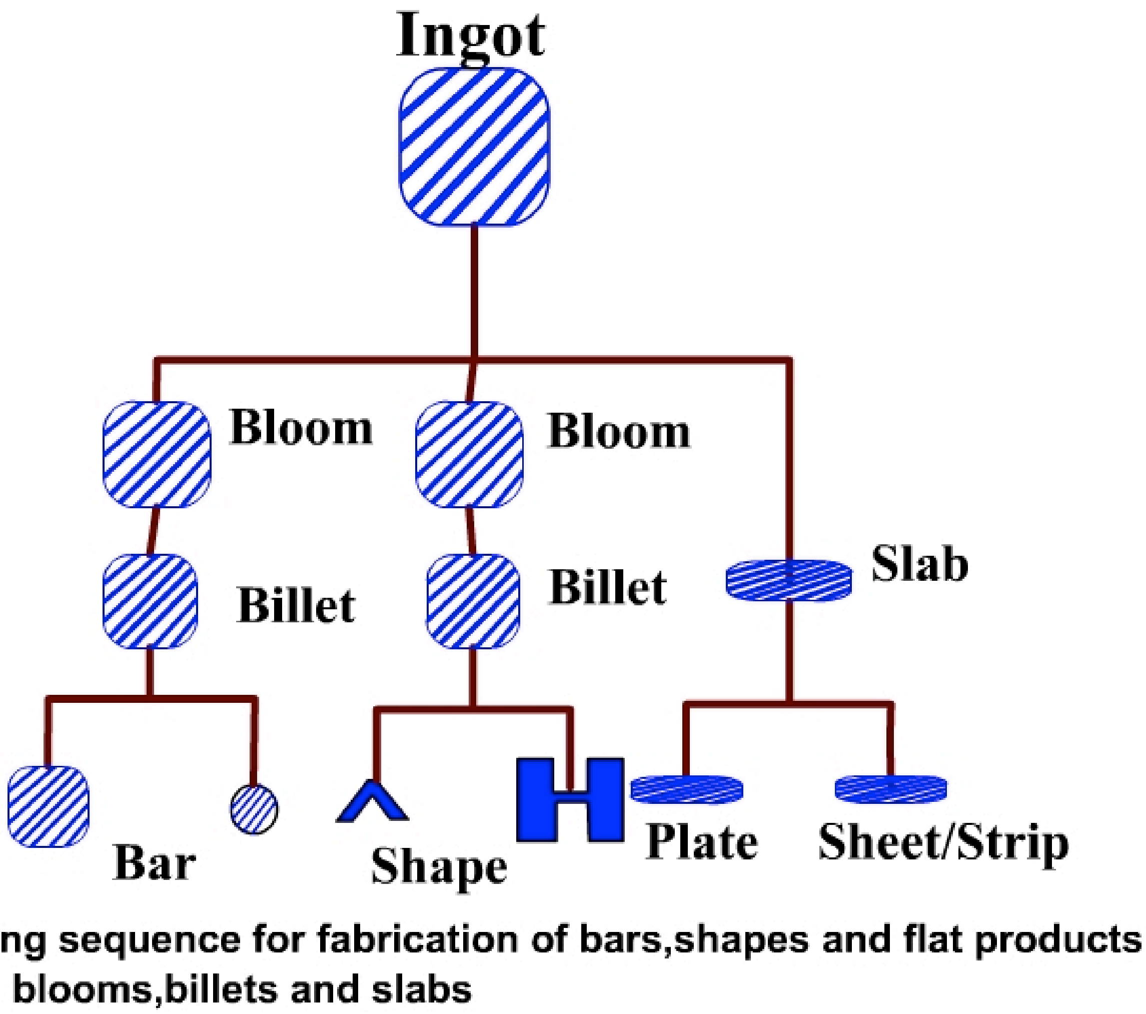

Fig.1.1.1: Flow diagram showing Rolling of different products

Plates have thickness greater than 6 mm whereas strips and sheets have less than 6 mm thickness.

Sheets have greater width and strip has lower width – less than 600 mm.

1.2 Rolling mills:

Rolling mill consists of rolls, bearings to support the rolls, gear box, motor, speed control devices, hydraulic systems etc. The basic type of rolling mill is two high rolling mill. In this mill, two opposing rolls are used. The direction of rotation of the rolls can be changed in case of reversing mills, so that the work can be fed into the rolls from either direction. Such mills increase the productivity. Non reversing mills have rolls rotating in same direction. Therefore, the work piece cannot be fed from the other side. Typical roll diameters may be 1.4 m.

A three high rolling mill has three rolls. First rolling in one direction takes place along one direction. Next the work is reversed in direction and fed through the next pair of roll. This improves the productivity.

Rolling power is directly proportional to roll diameter. Smaller dia rolls can therefore reduce power input. Strength of small diameter rolls are poor. Therefore, rolls may bend. As a result, largerdia backup rolls are used for supporting the smaller rolls. Four high rolling mill is one such mill. Thin sections can be rolled using smaller diameter rolls. Cluster mill and Sendzimir mill are used for rolling thin strips of high strength materials and foils [0.0025 mm thick]. The work roll in these mills may be as small as 6 mm diameter – made of tungsten carbide. Several rolling mills arranged in succession so as to increase productivity is called rolling stand. In such arrangement, anuncoiler and windup reels are used. They help in exerting back tension and front tension.

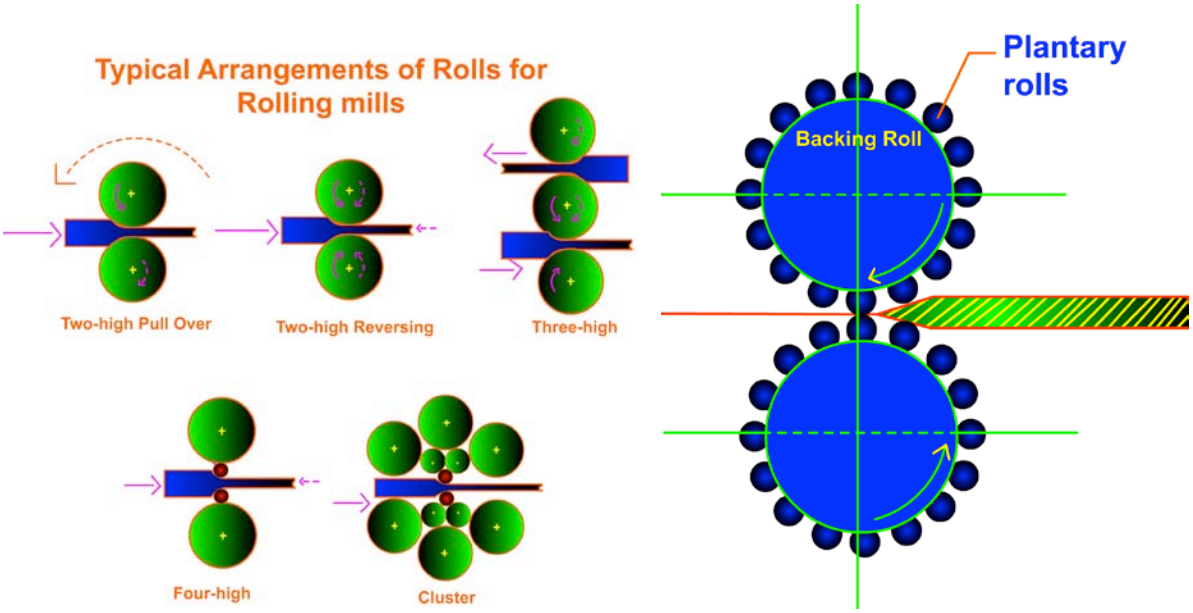

Fig. 1.2.1: Rolling mills

Planetary mill has a pair of large heavy rolls, surrounded by a number of smaller rolls around their circumference. In this mill, a slab can be reduced to strip directly in one pass. Feeder rolls may be needed in order to feed the work piece into the rolls.

Merchant mill is specifically used for rolling bars.

Hot rolling is usually done with two high reversing mill in order to breakdown ingots into blooms and billets. For increased productivity, universal mill has two vertical rolls which can control the width of the work simultaneously.

Non ferrous materials are cold rolled into sheets from hot rolled strips. Four high tandem mills are generally used for aluminium and copper alloys. In order to achieve upto 90% reduction in thickness in cold rolling, a series of rolling mills may be used to share the total reduction.

One important application of cold rolling is the removal of yield point from mild steel sheets using skin pass rolling [temper rolling]. In this the steel sheet is given a light reduction of 0.5 to 1.5% . Such a process eliminates yield point elongation. If yield elongation of steel occurs during sheet metal operation, such as deep drawing, the surface of the sheet metal becomes rough due to formation of Luder bands, also called stretcher strains.

Flatness of rolled sheets can be increased by roller leveling. In this process, the sheet is passed between a pair of rolls which are driven by individual motors and are slightly offset.

Rolls should have high stiffness, hardness and strength. Cast iron, cast steel and forged steel are also used as rolls.

1.3 Grain structure in rolling:

When the wrought or cast product gets hot rolled, the grain structure, which is coarse grained, becomes finer in size, but elongated along the direction of rolling. This type of textured grain structure results in directional property [anisotropy] for the rolled product. In order to refine the grains, heat treatment is performed immediately after rolling, which results in recrystallization after rolling.

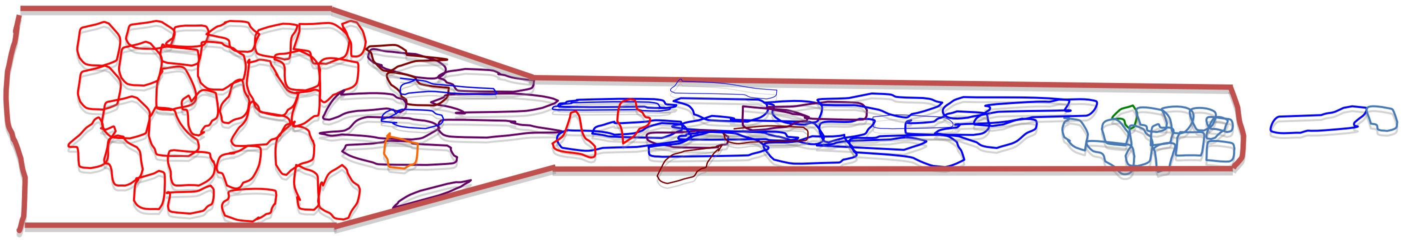

Fig. 1.3.1: Variation of grain structure, size during longitudinal rolling

1.4 Special rolling processes:

Bulk deformation processes such as shape rolling, thread rolling, roll piercing, ring rolling also use pair of rolls. Some of such important processes are discussed briefly below:

Thread and gear rolling:

Threads on cylindrical work pieces can be cold formed using a pair of flat dies or cylindrical rolls under reciprocating or rotary motion. Screws, bolts and other externally threaded fasteners are produced by thread rolling. Thread rolling is a high productivity process involving no loss of material. Due to grain flow in thread rolling strength is increased. Surface finish of rolled threads is very good. Gears can also be produced by the thread rolling process. Compressive stresses introduced during the process isfavourable for fatigue applications. Auto power transmission gears are made by thread rolling.

Shape rolling:

Structural sections such as I-sections, rails, channels can be rolled using set of shaped rolls. Blooms are usually taken as raw materials for shape rolling. Multiple steps are required in shape rolling.

Ring rolling:

Smaller diameter, thicker ring can be enlarged to larger diameter, thinner section by ring rolling. In this process, two circular rolls, one of which is idler roll and the other is driven roll are used. A pair of edging rollers are used for maintaining the height constant. The ring is rotated and the rings are moved closer to each other, thereby reducing the thickness of ring and increasing its diameter. Rings of different cross-sections can be produced. The major merits of this process are high productivity, material saving, dimensional accuracy and grain flow which is advantageous. Large rings for turbines, roller bearing races, flanges and rings for pipes are some of the applications of this process.

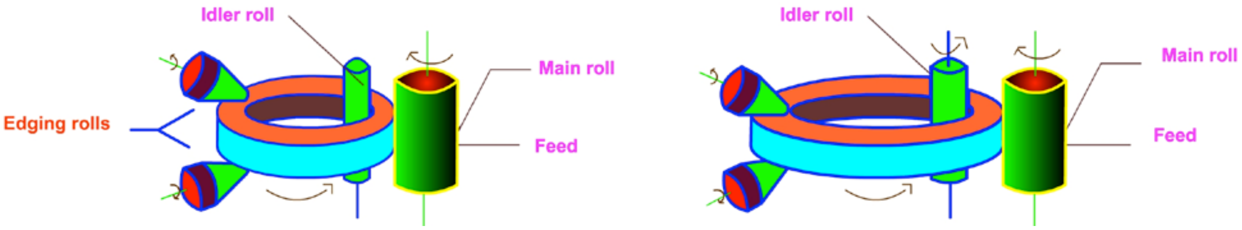

Fig. 1.4.1: Ring rolling process

Tube piercing:

Rotary tube piercing is used for producing long thick walled tubes. Cavity forms at the center due to tensile stress, in a round rod when subjected to external compressive stress – especially cyclic compressive stress.

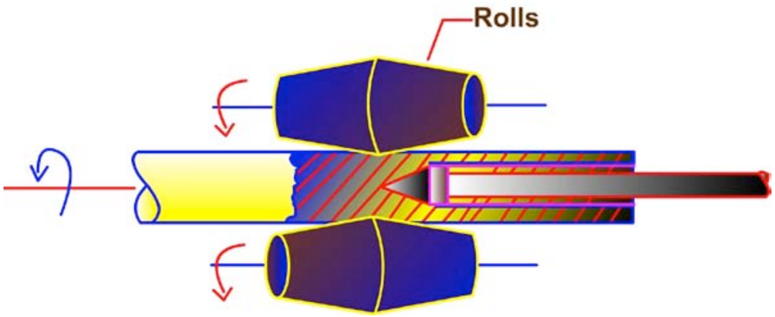

Fig.1.4.2: Mannesmann Mill

The Mannesmann process makes use of a tube piercing in rotary mode. A pair of skewed rolls are used for drawing the work piece inside the rolls. The roll axes are oriented at 6 degrees with reference to axis of work piece. A mandrel is used for expanding the central hole, and sizing the inner diameter. Pilger mill uses reciprocating motion of both work and mandrel to produce tubes. Work is periodically rotated additionally.

Analysis of strip rolling - 1:

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1. Analysis of strip rolling - 1: 3

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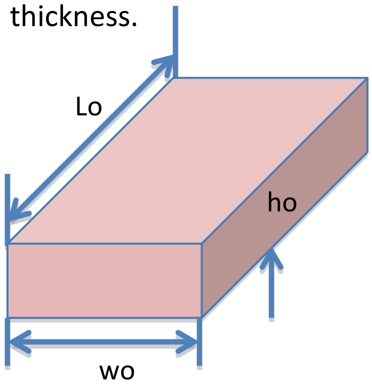
1. Analysis of strip rolling - 1:

1.1 Geometric Relations:

Consider the rolling of a strip of initial thickness h_o, between a pair of rolls of radius R. The rolls are rotating in same direction. The strip is reduced in thickness to h_f with width of the strip assumed to remain constant during rolling – because width is much larger than thickness. Flat rolling is a plane strain compression process.



Draft refers to reduction in thickness.

Draft = h_o-h_f

Reduction (r) is the ratio of thickness reduction

$R = (h_o-h_f)/ h_o = 1 - h_f/ h_o$ ----------------------1

If the change in width of the strip is taken into consideration, we can find the final width by applying the volume constancy principle.

Volume of material before rolling = volume after rolling.

That is, $h_oL_ow_o = h_fL_fw_f$-----------------------------------2

L is length of the strip

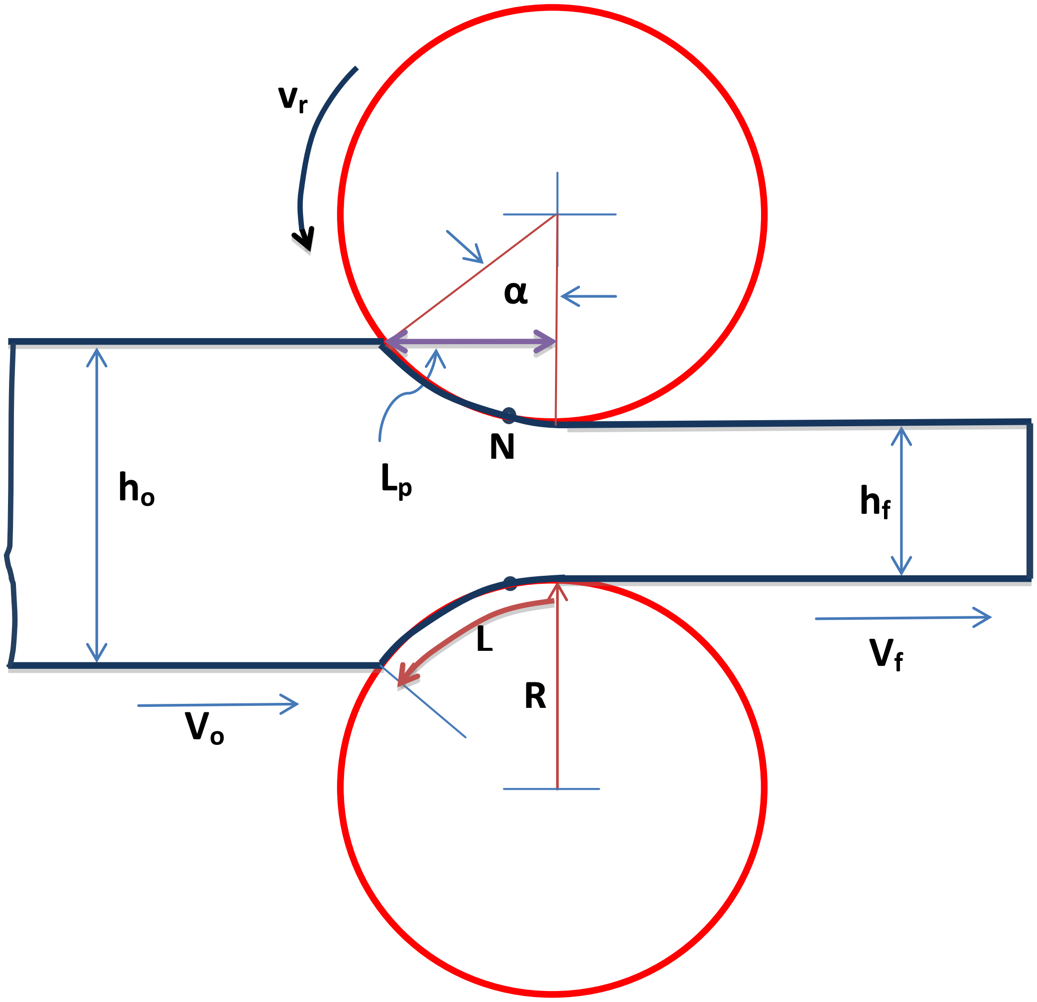


Fig. 2.1.1: Strip rolling process – geometry and parameters

Flat rolling-terminology:

R – roll radius

L – contact arc length

v_f - velocity of strip at roll exit

N – neutral point

L_p – projected arc length

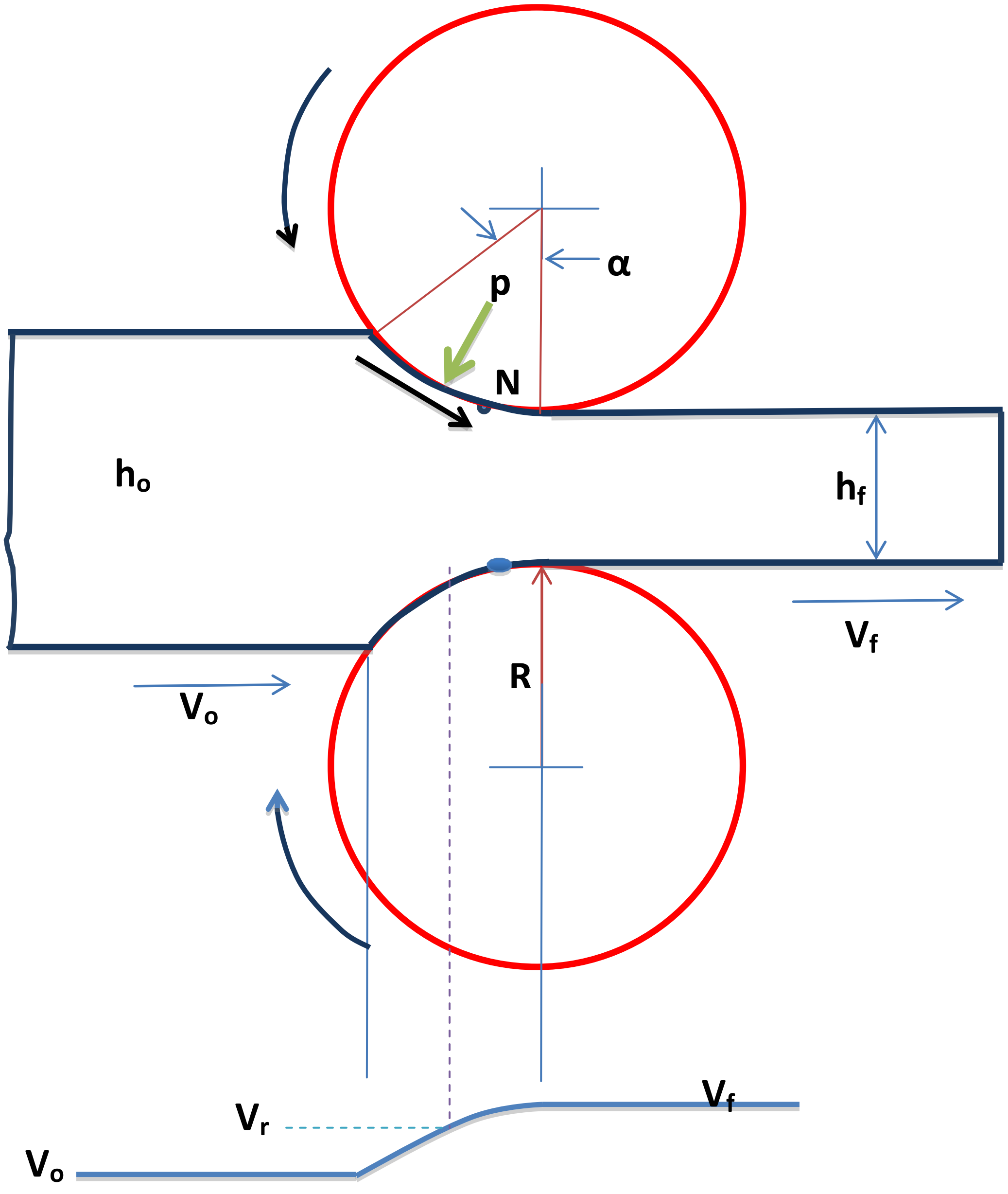
h_o – strip initial thickness

h_f– strip final thickness

α – angle of bite

v_r – velocity of roll

v_o – velocity of strip at entrance to roll



$V_f > V_r > Vo$

Fig. 2.1.2: Velocity variation in rolling process

From the diagram above, we note that the velocity of the strip increases from V_o to V_f as it passes through the rolls. This velocity increase takes place in order to satisfy the principle of volume constancy of the billet during the deformation process.

i.e. $h_o \cancel{w} V_o = h_f \cancel{w} V_f \rightarrow \frac{V_f}{V_o} = \frac{h_o}{h_f}$------------------- 3

w is width of the strip, which is assumed to be constant during rolling.

From equation 3 we find that the strip velocity increases during rolling, as it passes between the rolls. At some section the velocity of rolls and strip velocity are equal. This point is called neutral point. Ahead of neutral point, the strip is trailing behind the rolls. Beyond the neutral point the strip leads the rolls.

Frictional shear stress τ acts tangential to the rolls at any section along the arc of contact between rolls and strip.However, the direction of τ reverses at the neutral point. Between the entry section of the roll gap and the neutral section, the direction of friction is the same as the direction of motion of the strip – into the roll gap. Therefore, the friction aids in pulling the strip into the rolls in this part of the travel.

The direction of friction reverses after the neutral point, as the velocity of strip is higher than the velocity of the rolls. Friction force opposes the forward motion of the strip in sections beyond the neutral section. However, the magnitude of the friction acting ahead of neutral section is greater than that beyond the neutral section.

Therefore, the net friction is acting along the direction of the strip movement, thereby aiding the pulling of the strip into the roll gap.

The forward slip is defined as the difference in velocity between the strip at exit and roll divided by roll velocity.

i.e. $FS = (V_f - V_r)/V_r$ ------------------4

At roll exit the forward slip is positive, meaning that the work piece moves faster than roll here.

The projected arc length [L_p], which is the length of the straight line got by projecting the arc of contact onto a horizontal line or plane.

From the geometry of the arc of contact, we can getL_p as below:

$L_p^2 = R^2 - (R - \Delta h)^2$

Ignoring power of small quantity, Δh, etc, we get

$L_p = \sqrt{R\,\Delta h}$ ----------------------5

Where Δh is the draft and is= $h_o - h_f$

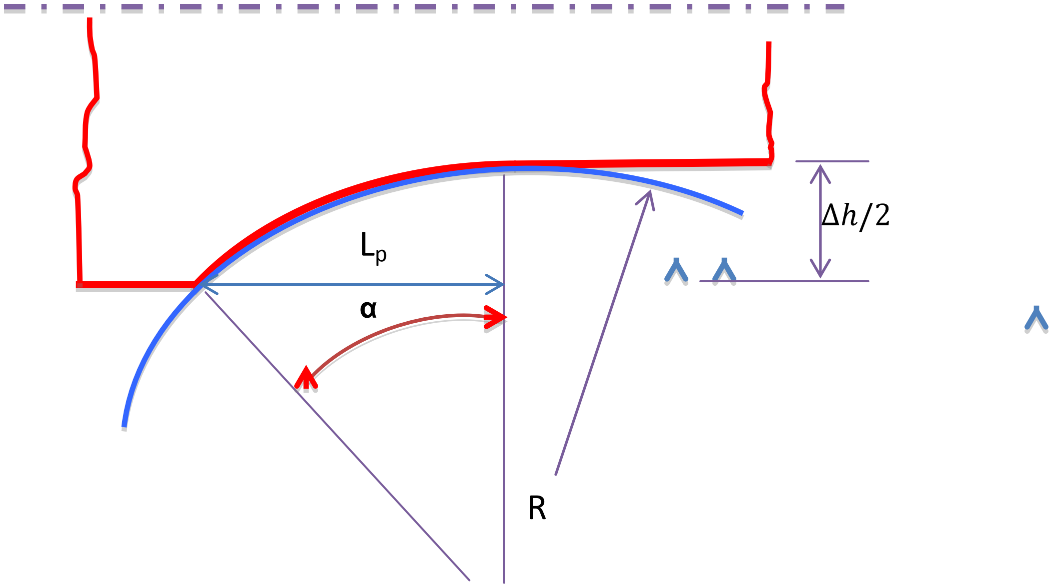


Fig. 2.1.3: Geometry of roll deformation zone

1.2 Limiting condition for friction between roll and work:

The rill exerts a normal pressure p on the work. This pressure may be imagined to be the pressure exerted by the work piece on the rolls to separating them.

Due to the roll pressure a tangential friction shear stress is induced at the interface contact between roll and work piece.

This friction stress can be written as:

$\tau = \mu p$

Sliding friction is assumed between roll and work. At the entry section, if the forces acting on the strip are balanced, we get:

$p \sin\alpha = \mu\, p \cos\alpha \rightarrow$ area over which both forces are acting is the same

If the work piece is to be pulled into the rolls at entry section, the following condition is to be satisfied:

$\mu\, p \cos\alpha \geq p \sin\alpha \rightarrow \mu \geq \tan\alpha \rightarrow \tan\alpha_{max} = \mu$ **--------------6**

Or the minimum condition for work to be pulled into the rolls can be written as:

$\mu = \tan\alpha$

If the tangent of angle of bite exceeds the coefficient of friction, the work piece will not be drawn into the roll gap

$\alpha = 0$ indicates rolling**.**

From geometry of the roll-strip contact, we can write:

$\tan\alpha_{max} = L_p/(R- \Delta h/2) \approx \sqrt{R\Delta h}\,/R = \sqrt{\Delta h/R} = \mu$ **--------7**

We can infer from the above equation that for the same angle of bite [same friction condition], a larger roll will enable thicker slab to be drawn into the roll gap. This is because for large radius roll the arc length is larger, and hence L_p is larger.

From equation 7 above we find:

$\Delta h_{max} = \mu^2 R$ **------------8**

From equation 8 we can conclude that decreasing the roll radius reduces the maximum achievable reduction in thickness of strip.

We can also conclude that higher coefficient of friction can allow larger thickness of the strip to be drawn into the roll throat. Longitudinal grooves are made on the roll surface in order to increase friction. This enables the breakdown of large thickness ingots during hot rolling.

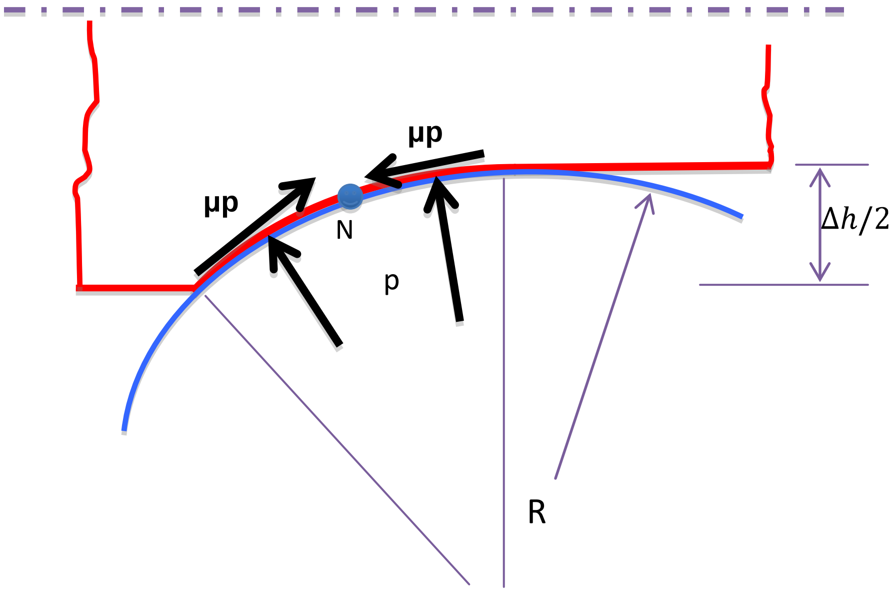


Fig.1.2.1: Roll pressure and frictional shear stress acting at the roll-work piece interface

Example: What is the maximum possible reductionthat could be achieved on a strip of250 mm thick, if it is cold rolled using rolls of diameter 600 mm with a coefficient of friction value of 0.09. What is the corresponding thickness if the rolling is carried out hot with μ=0.5?

Solution: We know that the maximum reduction is given by: $\Delta h_{max} = \mu^2 R$ **(Equation 8)**

For cold rolling, maximum reduction = 4.86 mm

For hot rolling, maximum reduction = 150 mm, which is almost 30 times the reduction in cold rolling.

Analysis of strip rolling - 2:

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1.Analysis of strip rolling - 2:

1.1 Simplified analysis:

The parameters which influence the rolling process are: roll diameter, friction, material flow stress, temperature of working etc.

Without considering friction, we can get the rolling load, approximately, from the material flow stress and the area of contact between roll and strip.

Roll pressure $p = \overline{Y_f}$ -------------------- **9**

Where $\overline{Y_f}$ is average flow stress in plane strain compression.

It is given as: $\overline{Y_f} = \frac{2}{\sqrt{3}} Y$ ------------------ **10**

Here Y is yield strength of the material

Rolling load F is now written as:

$F = \overline{Y_f}\, L p\, w_m = \overline{Y_f}\sqrt{R\Delta h}\, w_m$--------------------------- 11

w_m is the average width of the strip

We have assumed that the area over which the roll force is acting is the projected area of the arc of contact. Moreover, the above equation is for a single roll.

As we see from the above equation, the roll force increases with increase in roll radius or increase in reduction of thickness of the strip (Δh).

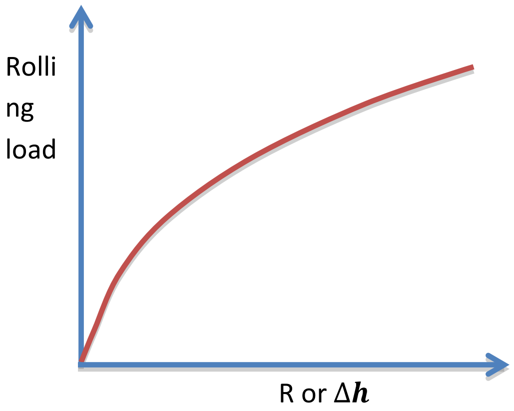

Fig. 1.1.1: Variation of rolling load with roll dia or strip thickness reduction

Alternatively, we can write the average flow stress based on true strain during rolling. For a material which obeys power law relation between plastic stress and strain, in the form: $\sigma = k\,\varepsilon^n$, average flow stress, Y'_f is given by:

$$\boldsymbol{Y'_f = \frac{K\varepsilon^n}{1+n}} \qquad \textbf{------------------- 12}$$

The true strain in rolling is given as:

$$\varepsilon = ln\frac{h_o}{h_f} \qquad \text{---------- 13}$$

Now, roll force F = $\boldsymbol{Y'_f L_p w_m}$ **--------------------14**

The above equation is based on the assumption that the material work hardens. In cold rolling, the work material gets work hardened considerably. Therefore, the above equation is more appropriate for cold rolling. The mean flow stress is determined from plane strain compression test, which is discussed in earlier module. It is assumed that the rolls do not undergo elastic deformation.

1.2 Slab analysis of strip rolling with friction – another approximate method:

Consider the rolling of a strip of initial thickness ho. The interface between the roll and work has sliding friction with constant coefficient of friction. We assume that the roll pressure is constant over the arc of contact.The strain on the work material is plane strain – no strain in width direction. Further, we assume that there is no elastic deformation of work and also, the deformation of work is homogeneous.

To apply the slab analysis to the rolling processes, we assume that the rolling is plane strain compression process. Further, the contact surface between roll and work piece is equal to the projected area of the arc of contact.

Further, we approximate the deformation zone as a rectangular shape, instead of conical shape and apply the analysis for plane strain compression.

Assume that the deformation volume of the work piece is in the form of rectangular prism of width L_p, height $\bar{h} =$ (h_o+h_f)/2 and depth unity, as shown in figure

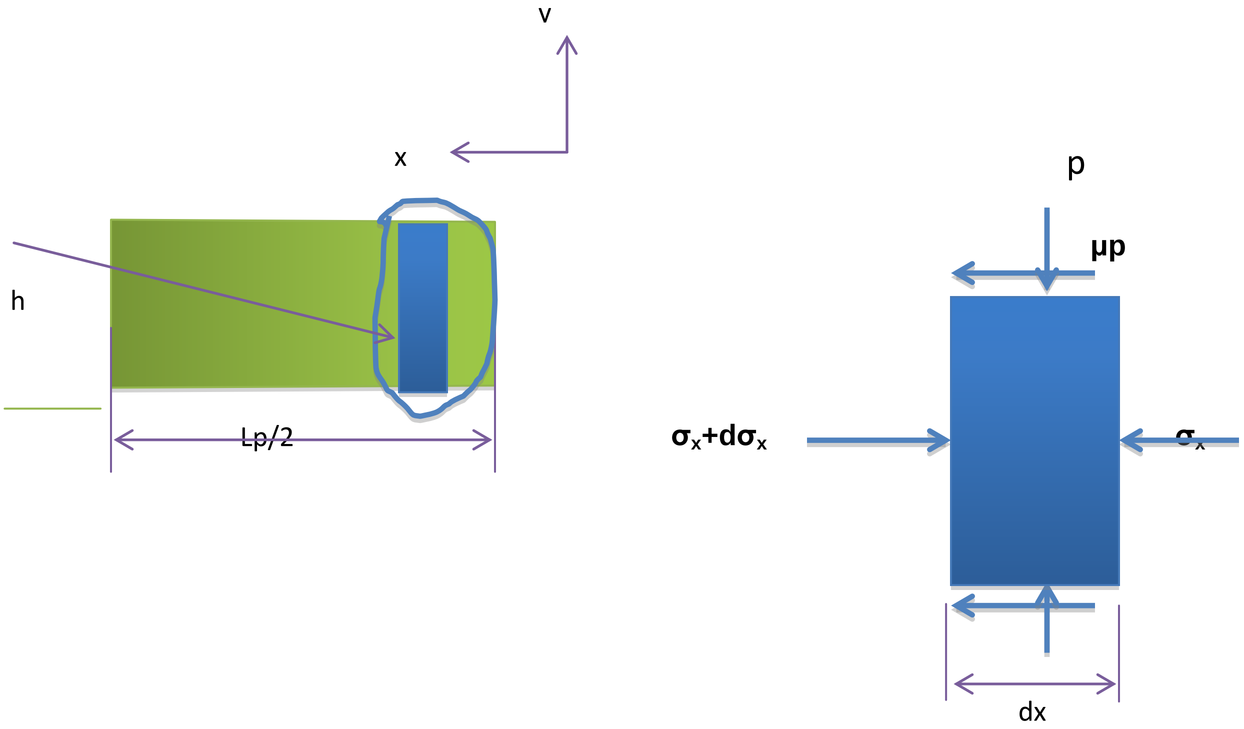

Fig. 1.2.1: Stresses acting on elemental strip under plane strain rolling

Consider an elemental strip of width dx, height h and depth of unity. The various stresses acting on the element are as shown in figure.

p is roll pressure, **μp**isthe shear stress due to friction, σ_x is normal stress acting on the outward face of the element, $\sigma_x + d\sigma_x$ is the stress acting on inner face of the element.

Writing the force balance along the x axis,

$-(\sigma_x + d\sigma_x)h + \sigma_x h = 2\mu p dx$ ---------------------------15

$d\sigma_x h = \; -2\mu p dx$ --------------------------------16

Applying the Tresca yield criterion, assuming that p and σ_x are principal stresses,

$\sigma_x + p = Y' \rightarrow \sigma_x = -p + Y'$, --------------------17

where Y' is plane strain flow stress which is given by:

Y’ = $\frac{2}{\sqrt{3}}Y$

Note: we have taken p as negative here

And also we have: $d\sigma_x = dp$ ------------------18

Substituting equation into equation we have:

$\frac{dp}{p} = \frac{2\mu dx}{h}$ -----------19

On integration we get:

ln p = $\frac{2\mu x}{h} + A$ ---------------------20

To solve for the constant A, we can apply the boundary condition:

AT x = 0, $\sigma_x = 0$ and from Tresca criterion, we have:

p = Y’ at x=0

Applying this in equation 20 we get: A = ln(Y’)

Substituting the expression for A in equation we get:

ln(p/Y’) = $\frac{2\mu x}{h}$ Or $\frac{p}{Y\prime} = e^{\frac{2\mu x}{h}}$ -------------------------------21

To get average pressure we can write:

$\bar{p} = \frac{2}{L_p}\int_0^{\frac{L_p}{2}} pdx$, Because: $\frac{\bar{p}L_p}{2} = \int_0^{\frac{L_p}{2}} pdx$

Substituting for p from equation 21 and integrating we get:

$$\frac{\bar{p}}{Y\prime} = \frac{\bar{h}}{\mu L_p}\left(e^{\frac{\mu L_p}{\bar{h}}} - 1\right)$$ ---------------------22

The above equation gives the approximate average rolling pressure for plane strain rolling process, neglecting the curvature of the strip as it passes between the rolls.

The rolling load can be determined from the equation 22 by noting that the area of contact is taken as projected length of contact multiplied by the depth of the work piece.

From the above equation we understand that the rolling load increases with reduction in the height h of the work or increasing in rill diameter. Below a certain minimum height of the strip(below a critical thinning), the rolling load increases to very high value, because the resistance of the sheet increases to very high values. As a result, we may not be able to roll the sheet. Instead the sheet just gets pushed in between rolls, without appreciable reduction in thickness. In order to roll thin sheets, we can use rolls of smaller diameter, backed up by large diameter rolls. Also we understand that the length of arc of contact decreases with roll radius.

Please note that as the coefficient of friction increases, the rolling load also increases.

Example: A 35 mm thick steel slab is hot rolled using a 900 mm roll. There is a reduction of 40% on the thickness. The coefficient of friction is 0.5. The material flow stress increases from 200 MPa at the entrance of the rolls to 280 MPa at the exit. What is the rolling load calculated by the approximate method of analysis? Assume a constant width of 800 mm for the slab. Roll flattening can be ignored.

Solution: Equation 22 gives the average rolling pressure

$$\frac{\bar{p}}{Y'} = \frac{\bar{h}}{\mu L_p}(e^{\frac{\mu L_p}{\bar{h}}} - 1)$$

Let us take Y’ as average of the flow stress at exit and entry.

Y’ = 240 MPa

(ho-hf)/ho = 0.4 Therefore, hf = 21 mm

$\bar{h}$= (21+35)/2 = 28 mm

Lp = projected arc length = $\sqrt{R\Delta h}$ = 112.25 mm

Average roll pressure = 205.73 MPa

Rolling force = 205.73X112.25X800 = 18.5 MN

Analysis of cold rolling – a more accurate method

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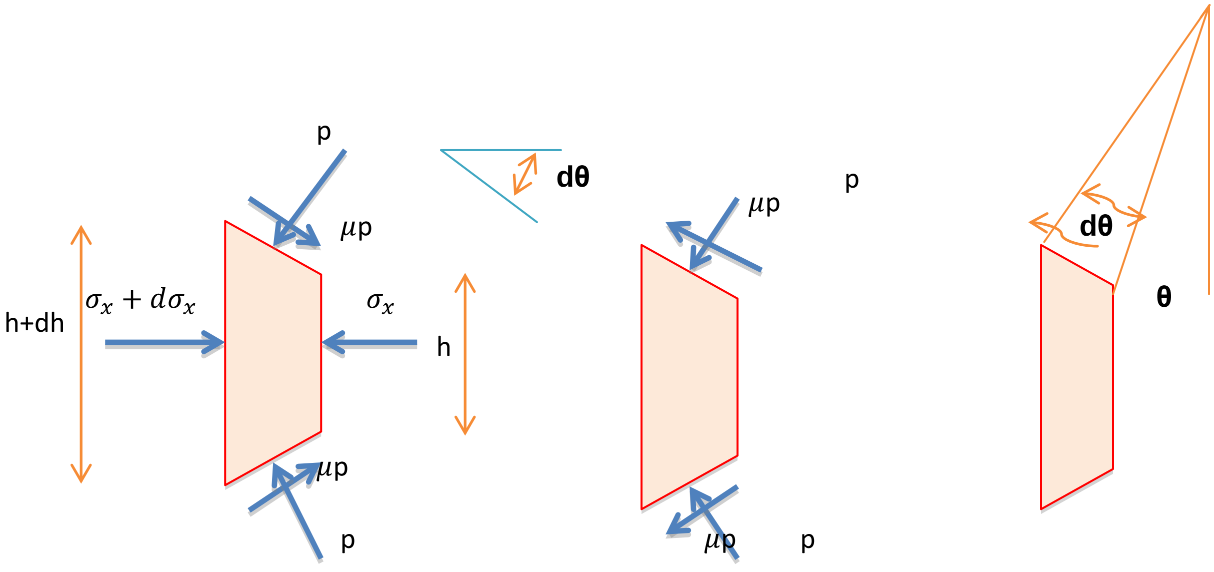
1.Analysis of cold rolling – a more accurate method:

1.1 Rolling of strip – more accurate slab analysis

The previous lecture considered an approximate analysis of the strip rolling. However, the deformation zone in rolling process is very complex and is curved. Therefore, we have to consider the various states of stresses acting, considering the curvature of the deformation zone. In cold rolling the work material is likely to undergo strain hardening as it comes out of the rolls. In the present lecture we consider the analysis considering various stresses acting on an elemental strip. Slab method of analysis is applied in order to obtain the rolling load in terms of the geometry of the deformation zone and roll diameter. We assume that rolls are not undergoing any elastic deformation.

Consider an elemental strip within the deformation zone, as shown below:

We assume that the rolling is plane strain process, as there is little spread of material along the width of the strip. Further, the friction coefficient remains constant through the rolling process.



Element before neutral section *After neutral section*

Fig. 1.1.1: Elemental strip taken from the rolling deformation zone

The element makes an angle of $d\theta$ with the roll centre.

Consider the element at an angle of θ from the line joining centres of the rolls

The following forces act on the element:

Normal roll pressure force: pR $d\theta$

Tangential friction force: μpR $d\theta$

The compressive forces: $\sigma_x h$ and $[\sigma_x + d\sigma_x]$[h+dh]

The normal and tangential forces can be resolved along the direction of rolling – x axis:

pR $d\theta sin\theta$ and μpR $d\theta cos\theta$

Making a force balance on the element shown above:

$[\sigma_x + d\sigma_x]$[h+dh] - $\sigma_x h$ - 2pR $d\theta sin\theta \pm$ 2μpR $d\theta cos\theta$ = 0 --------------23

Ignoring the products of small quantities, dividing by $d\theta$ and simplifying, we get:

$\frac{d(\sigma_x h)}{d\theta} = 2pR(sin\theta \pm \mu cos\theta)$ ----------------24

This equation is called von Karman equation.

In cold rolling, under low friction conditions angle θ is small [6 degrees]. We can approximately take; sinθ = θ and cosθ = 1. These approximates were proposed by Bland and Ford.

Now the above equation becomes:

$\frac{d(\sigma_x h)}{d\theta} = 2pR(\theta \pm \mu)$ -------------------25

From von Mises yield criterion applied to plane strain we have:

$\sigma_1 - \sigma_3 = \frac{2}{\sqrt{3}}Y$ --------26

In rolling, for small angle, the two principal stresses are: the roll pressure p and σ_x

Therefore, we have:

p - σ_x= $\frac{2}{\sqrt{3}}Y$ = Y' --------27

Substituting this in the above equation,

$\frac{d(p-Y\prime)h)}{d\theta} = 2pR(\theta \pm \mu)$ ----------------28

Or Y'h$\frac{d(\frac{p}{Y'})}{d\theta} - (p/Y' - 1)\frac{dY'h}{d\theta}$ = $2pR(\theta \pm \mu)$ --------------29

The second term on left hand side can be ignored because, Y'h is constant. That is, when h increases, Y' decreases and vice versa.

Now we have:$Y'h\ \frac{d(\frac{p}{Y'})}{d\theta} = 2pR(\theta \pm \mu)$ ----------30

$\frac{\frac{d}{d\theta}\left(\frac{p}{Y'}\right)}{\frac{p}{Y\prime}} = \frac{2R}{h}(\theta \pm \mu)$ ---------31

we can approximately write: h = h_f +Rθ^2

Substituting this in 31 and integrating we get the general solution to the above differential equation as:

$p = AY'\frac{h}{R}e^{\pm\mu H}$----------32

where H = 2 $\sqrt{\frac{R}{h_f}}$ $\tan^{-1}$[$\sqrt{\frac{R}{h_f}}\theta$] ---------32A

Applying the boundary conditions: At entry, $\theta = \alpha$ and H = H_o

AT exit, $\theta = 0$ and H = 0

We get the roll pressure as:

p = $Y'\frac{h}{h_o}e^{\mu(Ho-H)}$ at the entry ------33

p = $Y'\frac{h}{h_f}e^{\mu H}$ at exit -----------43

From the above expressions we note that the local rolling pressure depends on the angular position of the section and the height of the work, h. It is also dependent on R/h_fR/$h_f$is equivalent of a/h in forging. As this ratio increases, the rolling pressure also increases.

The total rolling force P can be evaluated by integrating the local rolling force over the arc of contact.

P = Rb$\int_0^\alpha pd\theta$, where b is width of the strip ----44

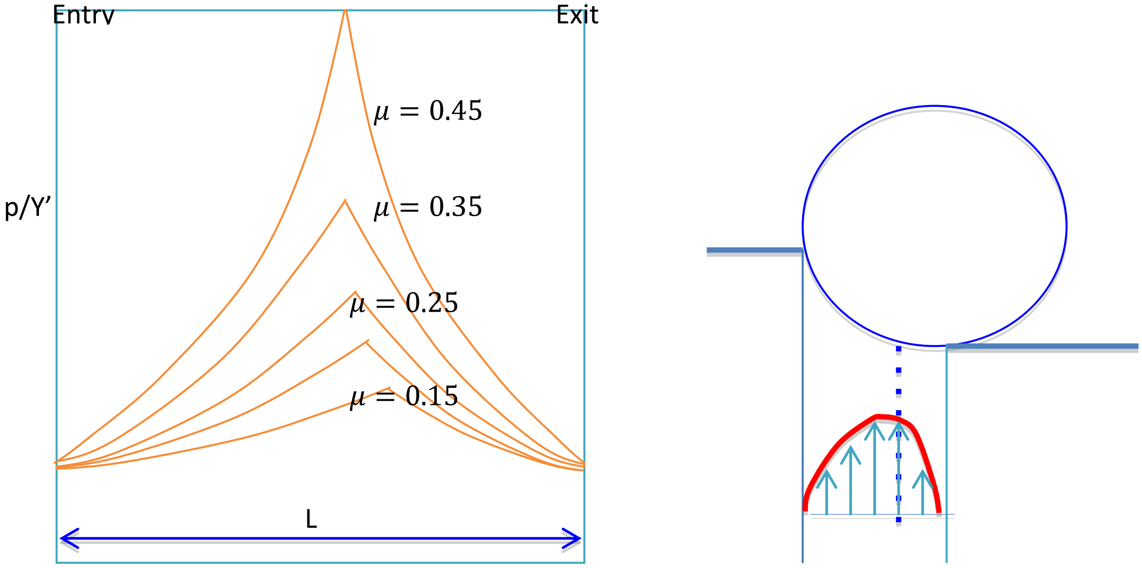


Fig. 1.1.2: Actual variation of roll pressure

The above figure shows the variation of the non-dimensional roll pressure with respect to the coefficient of friction – the friction hill. We observe that the roll pressure increases with increase in coefficient of friction. The area under the curves gives the total roll force. Further, we also observe that the neutral point also shifts towards the exit as the coefficient of friction reduces. As the friction gets reduced, there is slipping between the rolls and the work. Hence the relative velocity between roll and strip is in the same direction.

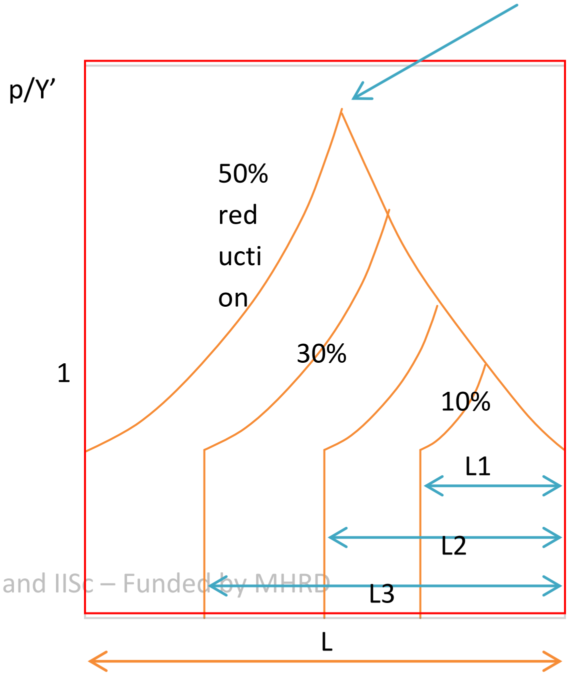


Fig.4.1.3: Roll Entry **pressure versus reduction in thickness**

The above figure represents the variation of roll pressure with respect to thickness reduction of the strip. As the reduction increases the roll pressure also increases. This is because, for larger reductions, the length of contact between roll and strip increases.

1.2 Determination of neutral point:

The neutral point can be determined by equating the roll pressure before neutral point to that after neutral point. Equating the equations 33 and 34 and solving for Hn,

$$H_n = \frac{1}{2}(H_o - \frac{1}{\mu} ln \frac{h_o}{h_f}) \quad \text{------45}$$

Substituting this in equation 32A and solving for θ,

$$\theta_n = \sqrt{\frac{h_f}{R}} \tan[\sqrt{\frac{h_f}{R}} \frac{H_n}{2}] \quad \text{---------------46}$$

Example:

Determine the rolling power required to roll low carbon steel strip, 250 mm wide, 12 mm thick, if the final thickness is 9 mm. Assume sliding friction between the rolls and work, with a coefficient of friction 0.12. The 250 mm radius rolls rotate at a speed of 300 rpm. Take k= 550 MPa, n = 0.26 for steel.

Solution:

We can take the average roll force for sliding friction condition as:

$$F = Lw\bar{Y}'(1+\frac{\mu L}{2h_{av}})$$

True strain = ε = ln(ho/hf) = 0.287

The average flow stress of the material = $k\varepsilon^n/1+n$ = 315.73 MPa

Plane strain flow stress Y' = $\frac{2}{\sqrt{3}}$Average flow stress = 364.58 MPa

hav = (12+9)/2 = 10.5 mm

L = $\sqrt{R\Delta h}$ = 27.39 mm

Rolling load F = 2.9MN

Roll torque = FXL/2

Power = $\pi NTorque$ = 1,25 MW

Hot rolling and rolling defects

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1. Hot rolling and rolling defects:

1.1 Front and back tensions:

We have seen that the rolling load is dependent on roll diameter, higher the roll dia, higher the roll force. Similarly, smaller reductions requires lower roll force. In order to reduce the roll force, we can reduce roll diameter, or reducing the friction. Another method of reducing rolling force is to apply a small tensile force on the strip. Application of tensile force longitudinally reduces the compressive yield strength of the material in the transverse direction. This is apparent from the Tresca yield criterion.

In rolling, tensile force in longitudinal direction is applied at the entry section through a feeder oruncoiler with braking system. Forward tension is applied at the exit section through the coiler by controlling the torque on it. Back tension can be included with the roll pressure at entry section as followed:

For entry zone: p = $(Y' - \sigma_b)\frac{h}{h_o}e^{\mu(Ho-H)}$ ------5.1

For section between neutral section and exit p = $(Y' - \sigma_f)\frac{h}{h_f}e^{\mu H}$ -----------5.2

As a result of application of front tension or back tension, the neutral point is shifted forward or backward. Front tension leads to shift of the neutral point forward, whereas, application of back tension shifts the neutral point backward. Application of both forward and back tensions reduce the total roll force. Hence the torque and power for rolling get reduced.

The figure below exhibits the effects of front and back tension on rolling pressure:

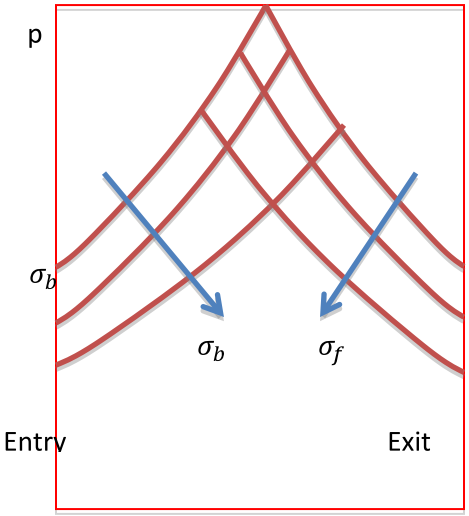


Fig. 1.1.1: Effect of front and back tensions on rolling load

1.2 Rolling force in hot rolling:

Material flow in hot rolling is less homogeneous. Strain rate also affects the flow stress of the material. Further, friction conditions are rather unpredictable. Friction coefficient in hot rolling may be high – ranges from 0.2 to 0.7. Strain rate in hot rolling can be found out from the expression:

$\dot{\varepsilon}$ = ln($\frac{h_0}{h_f}$) / time -------------- 5.3

Time can be writtenas : L/V, where V is velocity of roll, L is projected arc length.

Therefore, $\dot{\varepsilon}$ = (V/L)ln($\frac{h_0}{h_f}$) = (V/$\sqrt{R\Delta h}$)ln($\frac{h_0}{h_f}$) ------------------- 5.4

From flow curve we can determine the flow stress for the corresponding strain rate.

1.3 Total roll force:

Roll force is equal to roll pressure multiplied by area of contact between roll and work.

F = $\int_0^{\theta_n} pwRd\theta + \int_{\theta_n}^{\alpha} pwRd\theta$ ------------------------5.5

If friction is ignored, we can write an approximate expression for roll force as:

F = Lw$\overline{Y'}$ ---------------5.6

With friction:

F = Lw$\overline{Y'}$(1+$\frac{\mu L}{2h_{av}}$) ------5.7

Where, $h_{av}$is given by: (h_o+h_f)/2

1.4 Roll torque and power:

Roll torque can be estimated from the rolling force. Torque is equal to force multiplied by the radius at which the force acts.

We can assume that the roll force is acting perpendicular to the strip at a radius equal to one half of the projected arc length of contact.

For each roll, the torque is: T = FL/2

Roll power is given by:

Power = 2πNT ------------5.8

Torque can be more accurately determined from:

T = $\int_0^{\theta_n} pwR^2d\theta - \int_{\theta_n}^{\alpha} pwR^2d\theta$ --------------5.9

Here the minus sign is due to the fact that the friction force acts against the rolling direction beyond the neutral section. Total roll torque consists of the rolling torque plus the torque required to overcome friction in roll bearings plus torque at motor shaft plus torque for overcoming friction in transmission system.

Roll power is applied in order to deform the work material, to overcome friction in rotating parts etc.

1.5 Roll deflection and roll flattening:

Due to roll force, the rolls are subjected to deflection and they bend resulting in larger thickness at the centre of the rolled sheet and the edge being thinner. This defect is known as crown and camber. In order to avoid this rolls are given a slight curvature on surface by grinding so that the centre of the rolls has higher diameter than the edges. This is called cambering of rolls. The bulged rolls, when subjected to bending during rolling will produce flat sheets. For sheet rolling, normally camber of 0.5 mm on roll diameter is provided. Also during hot rolling, rolls get heated up and bulge out at the center, causing camber of the rolls. This is due to temperature variation between edges and the center of rolls. Roll camber has to be varied during rolling in order to take care of roll camber due to both thermal effects and roll deflection. This also avoids uneven roll wear – rolls wear more at edges than at center.

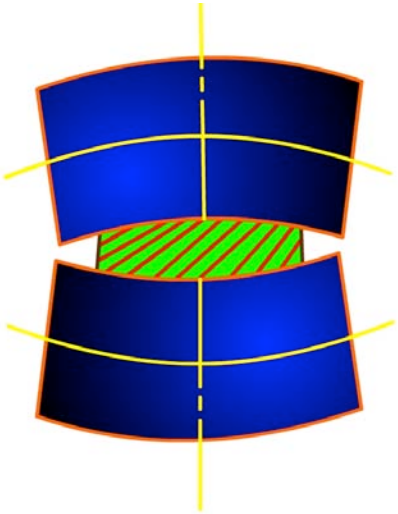


Fig. 1.5.1: Roll bending

Roll camber can be varied by 1] bending the work rolls by applying external force. 2] Shifting of work rolls laterally with respect to centerline of the strip, 3] using shaped rolls – rolls with profiles, 4] Rotation of the axis of the work roll with respect to axis of backup roll in horizontal plane – results in deflection of work roll ends, producing camber.

Roll flattening: There is increase in radius of curvature of rolls due to the roll pressure which causes elastic deformation of rolls. This is known as roll flattening. Roll flattening leads to increase in contact length and hence an increase in roll force. The distorted roll radius is given by:

$R' = R[1 + \frac{Cp'}{b(h_o - h_f)}]$ -------------5.10

$C = 16(1-\upsilon^2)/\pi E$. $C = 2.16 \times 10^{-11}$ Pa^{-1} for steel

P' is roll pressure with flattened roll. Higher the Young's modulus of the roll material, the lower is roll flattening.

The above equation requires iteration. While calculating rolling force, the value of flattened roll radius R’ has to be considered.

1.6 Spread:

Spread refers to the increase in width of rolled strips of low width to thickness ratios – square sectioned strips for example. Reducing the friction, increasing the roll radius to strip thickness ratio and using wider strips can reduce the roll spread. The spread given by w_o=w_f is given as:

$$\Delta w = 1.15\frac{\Delta h}{2h_o}[L - \frac{\Delta h}{2\mu}] \quad \text{----5.11}$$

Or in general, Δw= $w_o[e^{F\, ln(\frac{wf}{w1})} - 1]$ -------------5.12

A pair of vertical rolls called edger rolls can be used to reduce spread.

Lubrication:

Oils, soap emulsions, fatty acids are used as lubricants during hot rolling non-ferrous metals. Mineral oils, paraffin, fatty acids are used for cold rolling. Normally, foe ferrous alloys no lubricant is used.

1.7 Rolling mill control:

Production of continuous sheets and strips is one of the attractive features of modern rolling mills. However, control of sheet thickness and cross-section is a real challenge. In order to continuously monitor the thickness of sheets rolled, x-ray or gamma ray sensors are used. Precise control of gage of rolled sheets can be done by adjusting the roll gap. The following section explains the control.

Characteristic curves are drawn for the rolling process as shown below:

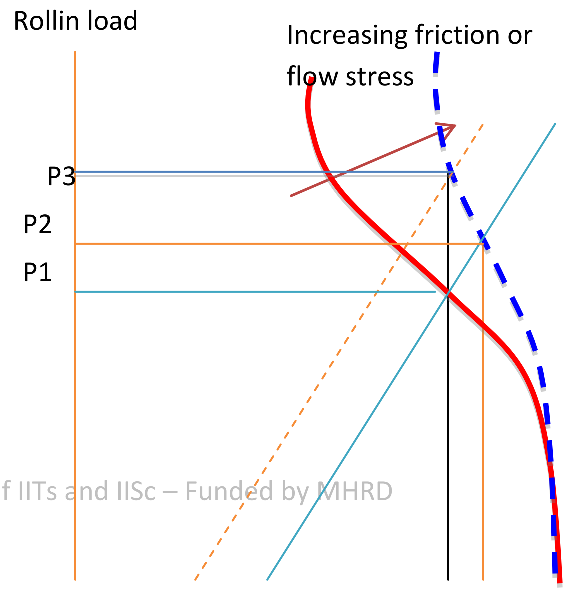


Fig. 1.7.1: Rolling mill control

From the above curves, we could understand the control of rolling mill. The solid curve, called plastic curve, represents the variation of rolling load with rolled thickness. As thickness reduces, roll force increases. This was shown earlier. The solid line represents the elastic deformation of the roll. The point of intersection of the solid curve and solid line on x axis represents the final rolled thickness obtained. The corresponding y axis value gives the rolling load. If for some reason, the friction coefficient increases. The plastic curve gets shifted to the right, as shown by dotted curve. As a result, without any control present, the final strip thickness increases to hf2 and the rolling load increases to p2. In order to maintain the thickness at hf1, the roll gap has to be reduced by shifting the elastic curve leftward. This is shown by the dotted straight line. Reducing the roll gap increases the roll pressure to p3. Gage control in multiple rolling mills is achieved through measurement of strip thickness using x-ray gage and adjusting the strip tension using feedback control system.

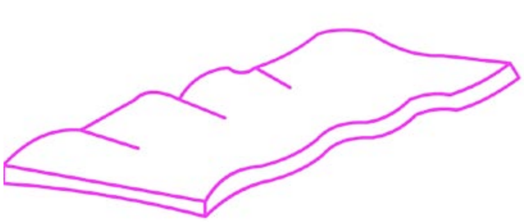
1.8 Rolling defects:

Mill spring is a defect in which the rolled sheet is thicker than the required thickness because, the rolls get deflected by high rolling forces. Elastic deformation of the mill takes place. If we use stiffer rolls, namely roll material of high stiffness or elastic constant, we could avoid mill spring. Normally elastic constant for mills may range from 1 to 4 GNm^{-1}.

Roll elastic deformation may result in uneven sheet thickness across. Roll material should have high elastic modulus for reducing the roll deformation. For producing very thin gage sheets like foils, small diameter rolls are used. They are supported with larger rolls. We can say the minimum thickness of rolled sheets achieved is directly proportional to roll radius, friction, flow stress.

Flatness of rolled sheets depends on the roll deflection. Sheets become wavy as roll deflection occurs.

If rolls are elastically deflected, the rolled sheets become thin along the edge, whereas at centre, the thickness is higher. Similarly, deflected rolls result in longer edges than the centre. Edges of the sheet elongate more than the centre. Due to continuity of the sheet, we could say that the centre is subjected to tension, while edges are subjected to compression. This leads to waviness along edges. Along the centre zipper cracks occur due to high tensile stress there. Cambering of rolls can prevent such defects. However, one camber works out only for a particular roll force.



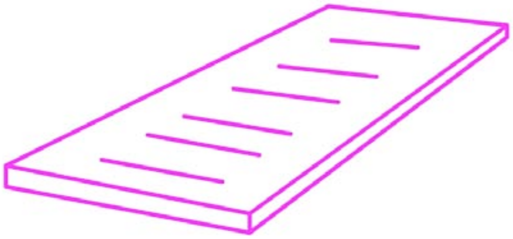


Fig 1.8.1:Wavy edge **Fig. 1.8.2: Zipper cracks**

In order to correct roll deflection for a range of rolling conditions, hydraulic jacks are used, which control the elastic deformation of rolls according to requirement.

Fig. 1.8.3: Centre crackFig. 5.8.4: Edge cracks

If rolls have excess convexity then the center of the sheet metal will have more elongation than the edges. This leads to a defect called centre buckle.

Fig. 1.8.5: Edge defect due to heavy reduction

Small thickness sheets are more sensitive to roll gap defects leading to greater defects. Thin strips are more likely to undergo waviness or buckling. These defects are corrected by doing roller leveling or stretch leveling under tension. Stretch leveling is carried out between roller leveler rolls.

During rolling the sheet will have a tendency to deform in lateral direction. Friction is high at the centre. Therefore, spread is the least at the centre. This leads to rounding of ends of the sheet. The edges of the sheet are subjected to tensile deformation . This leads to edge cracks. If the center of the sheet is severely restrained and subjected to excess tensile stress, center split may happen.

Non-homogeneous material deformation across the thickness leads to high secondary tensile stress along edge. This leads to edge cracks. Secondary tensile stresses is due to bulging of free surface. Edge cracks can be avoided by using edge rolls.

Due to non homogeneous flow of material across the thickness of the sheet, another defect called allegatoring occurs. This is due to the fact that the surface is subjected to tensile deformation and centre to compressive deformation. This is because greater spread of material occurs at center.

5.9 Residual stress in rolling:

Compressive stress is induced on the surface of rolled product if small diameter rolls are used or if smaller reductions are affected during rolling. Stress in the bulk of the strip is tensile in the above case. Larger reductions or rolling using large diameter rolls leads to tensile stress on the skin and compressive stress in the bulk of the metal. Stress relieving operation can be used to relieve the residual stresses of rolled products.

Types of extrusion and extrusion equipment

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1.Types of extrusion and extrusion equipment:

1.1 Introduction

Extrusion is a compressive deformation process in which a block of metal is squeezed through an orifice or die opening in order to obtain a reduction in diameter and increase in length of the metal block. The resultant product will have the desired cross-section. Extrusion involves forming of axisymmetric parts. Dies of circular on non-circular cross-section are used for extrusion. Generally, extrusion involves greater forming forces. Large hydrostatic stress in extrusion helps in the process by enhancing the ductility of the material. Metals like aluminium, which are easily workable, can be extruded at room temperature. Other difficult to work metals are usually hot extruded or warm extruded. Both circular and non circular parts can be obtained by extrusion. Channels, angles, rods, window frames, door frames, tubes, aluminium fins are some of the extruded parts.

Difficult to form materials such as stainless steels, nickel alloys are extruded due to its inherent advantage, namely, no surface cracking due to reaction between the billet and the extrusion container. Extrusion results in better grain structure, better accuracy and surface finish of the components. Less wastage of material in extrusion is another attractive feature of extrusion.

Lead pipes were extruded in late 1700’s in England. Later on lead sheathing of electric cables was done by extrusion.

1.2 Types of extrusion:

Extrusion ratio: It is the ratio of area of cross-section of the billet to the area of cross-section of the extrude.

R = Ao/Af

Another parameter used in extrusion is shape factor, ratio of perimeter to the cross-section of the part. An extruded rod has the lowest shape factor.

Extrusion is classified in general into four types. They are: Direct extrusion, indirect extrusion, impact extrusion and hydrostatic extrusion.

In extrusion process, the billet is placed in a container, pushed through the die opening using a ram and dummy block. Both ram and billet move.

Direct extrusion:

Direct extrusion, also called forward extrusion, is a process in which is the billet moves along the same direction as the ram and punch do. Sliding of billet is against stationary container wall.Friction between the container and billet is high. As a result, greater forces are required. A dummy block of slightly lower diameter than the billet diameter is used in order to prevent oxidation of the billet in hot extrusion. Hollow sections like tubes can be extruded by direct method, by using hollow billet and a mandrel attached to the dummy block.

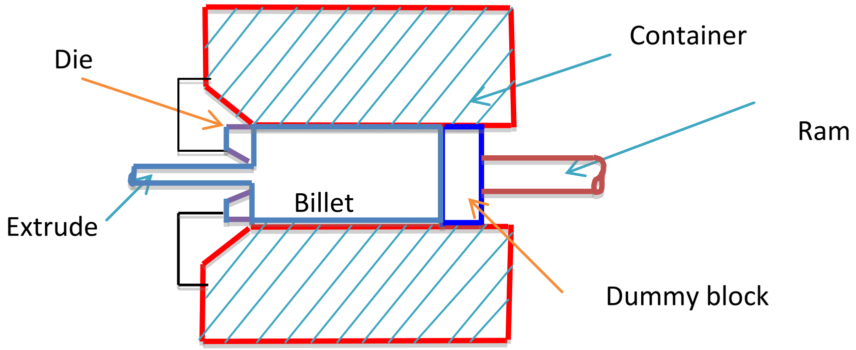

Fig. 1.2.1: Direct extrusion process

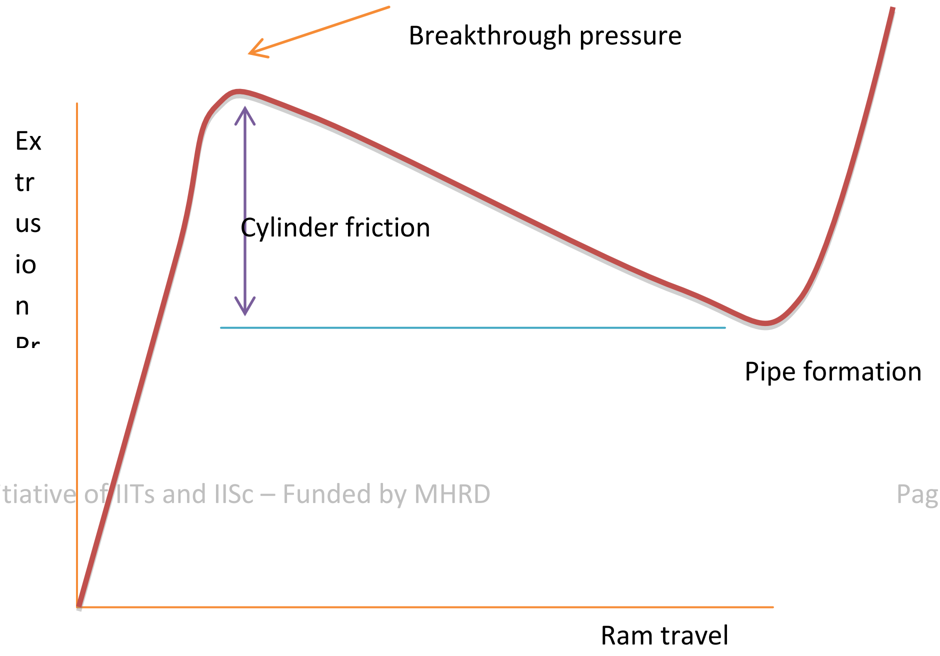

Fig. 1.2.2: Variation of extrusion force with ram travel in direct extrusion

Extrusion force, which is the force required for extrusion, in direct extrusion, varies with ram travel as shown in figure above. Initially the billet gets compressed to the size of container, before getting extruded. Also, initially static friction exists between billet and container. As a result the extrusion pressure or force increases steeply as shown. Once the billet starts getting extruded, it length inside the container is reduced. Friction between billet and container now starts reducing. Therefore, extrusion pressure reduces. The highest pressure at which extrusion starts is called breakthrough pressure. At the end of the extrusion, the small amount of material left in the container gets pulled into the die, making the billet hollow at centre. This is called pipe. Beyond pipe formation, the extrusion pressure rapidly increases, as the small size billet present offers higher resistance. As the length of the billet is increased, the corresponding extrusion pressure is also higher because of friction between container and billet. Therefore, billet lengths beyond 5 times the diameter are not preferred in direct extrusion.

Direct extrusion can be employed for extruding solid circular or non-circular sections, hollow sections such as tubes or cups.

Indirect extrusion:

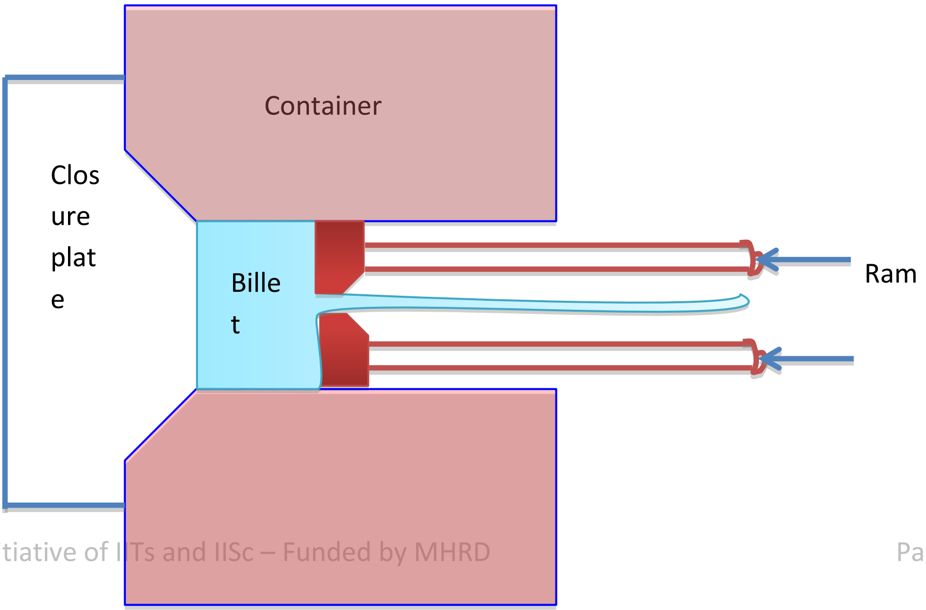

Fig. 1.2.3: Indirect extrusion

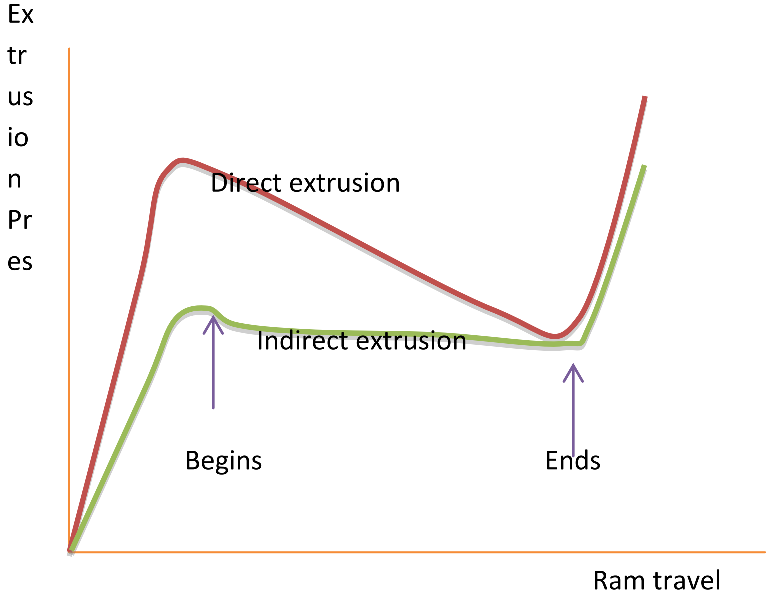

Fig. 1.2.4: Extrusion pressure versus ram travel for indirect and direct extrusion

Indirect extrusion (backward extrusion) is a process in which punch moves opposite to that of the billet. Here there is no relative motion between container and billet. Hence, there is less friction and hence reduced forces are required for indirect extrusion. For extruding solid pieces, hollow punch is required. In hollow extrusion, the material gets forced through the annular space between the solid punch and the container. The variation of extrusion pressure in indirect extrusion is shown above. As seen, extrusion pressure for indirect extrusion is lower than that for direct extrusion. Many components are manufactured by combining direct and indirect extrusions. Indirect extrusion can not be used for extruding long extrudes.

Hydrostatic extrusion:

In hydrostatic extrusion the container is filled with a fluid. Extrusion pressure is transmitted through the fluid to the billet. Friction is eliminated in this process because of there is no contact between billet and container wall. Brittle materials can be extruded by this process. Highly brittle materials can be extruded into a pressure chamber. Greater reductions are possible by this method. Pressure involved in the process may be as high as 1700 MPa. Pressure is limited by the strength of the container, punch and die materials. Vegetable oils such as castor oil are used. Normally this process is carried out at room temperature. A couple of disadvantages of the process are: leakage of pressurized oil and uncontrolled speed of extrusion at exit, due to release of stored energy by the oil. This may result in shock in the machinery. This problem is overcome by making the punch come into contact with the billet and reducing the quantity of oil through less clearance between billet and container. Hydrostatic extrusion is employed for making aluminium or copper wires-especially for reducing their diameters. Ceramics can be extruded by this process. Cladding is another application of the process. Extrusion ratios from 20 (for steels) to as high as 200 (for aluminium) can be achieved in this process.

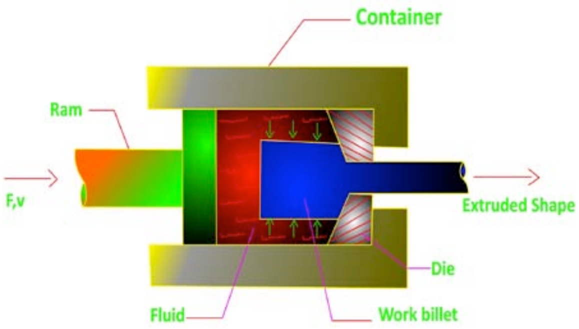

Fig. 1.2.5: Hydrostatic extrusion

Impact extrusion: Hollow sections such as cups, toothpaste containers are made by impact extrusion. It is a variation of indirect extrusion. The punch is made to strike the slug at high speed by impact load. Tubes of small wall thickness can be produced. Usually metals like copper, aluminium, lead are impact extruded.

Tube extrusion:

Employing hollow billet and a mandrel at the end of the ram, hollow sections such as tubes can be extruded to closer tolerences. The mandrel extends upto the entrance of the die. Clearance between the mandrel and die wall decides the wall thickness of the tube. The mandrel is made to travel alongwith the ram in order to make concentric tubes by extrusion.

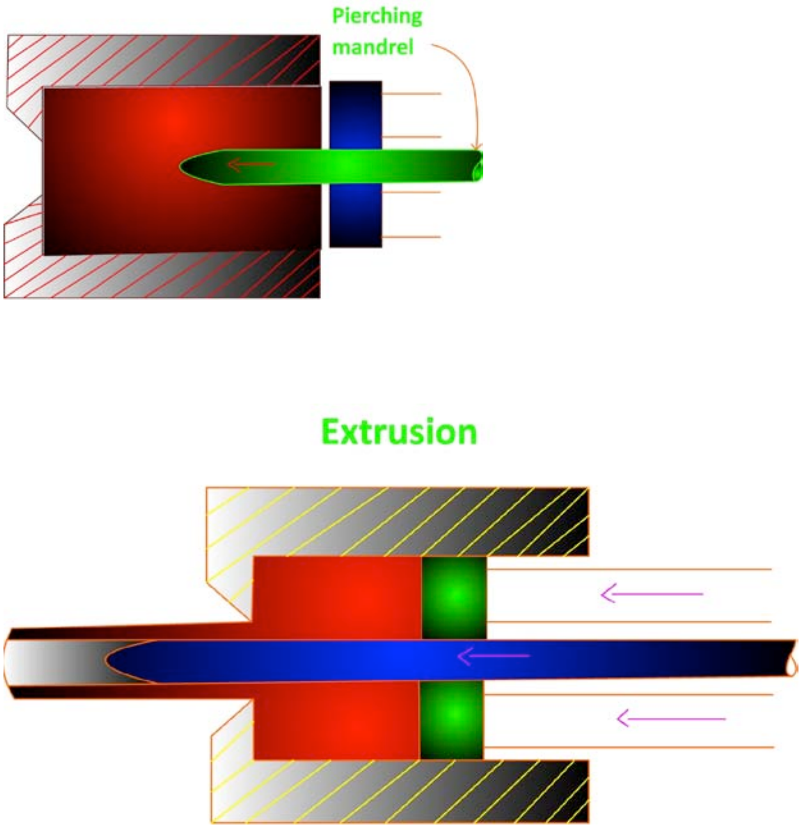

Fig. 1.2.6: Extrusion of tubes – piercing and extrusion

Tubes can also be made using solid billet and using a piercing mandrel to produce the hollow. The piercing mandrel is made to move independently with the help of hydraulic press. It moves along with the ram coaxially. First the ram upsets the billet, keeping the mandrel withdrawn. Next the mandrel pierces the billet and ejects a plug of material from central. Then the ram and mandrel together are moved in and extrude the billet.

Plug rolling and Mannesmann processes are also the other methods of producing seamless tubes.

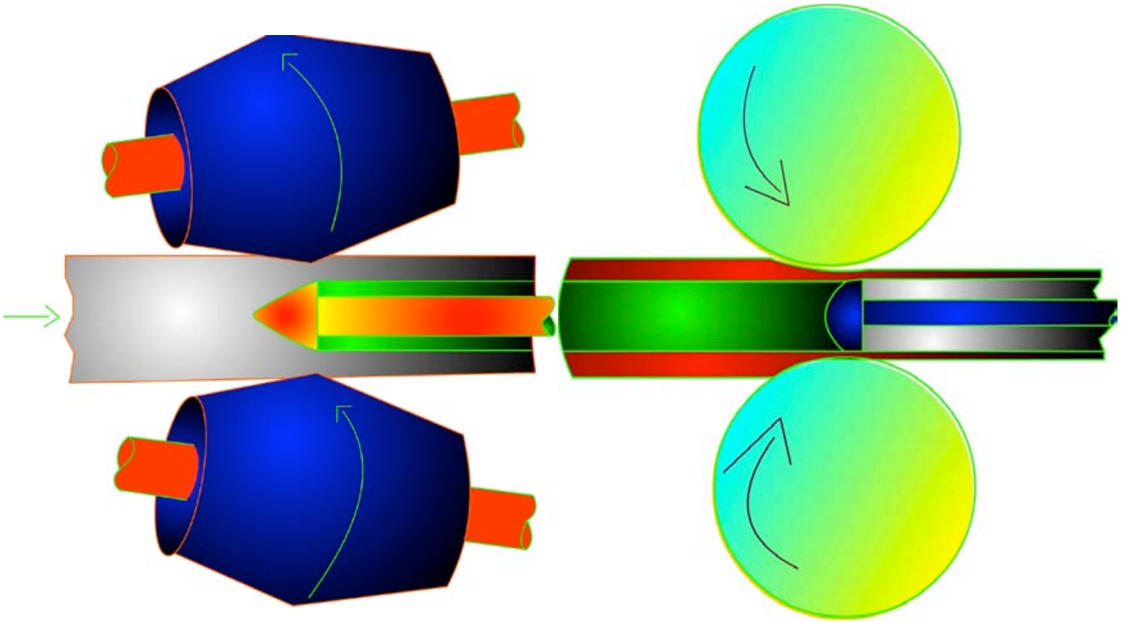

Fig. 1.2. 7: Mannesmann process and plug rolling process

Port hole extrusion is another method of producing tubes and hollow sections in aluminium, magnesium etc. In this method, a die with a number of ports and a central mandrel supported by a bridge is used. The billet is squeezed through the ports and flows in separate streams. After the die section the extruded streams are joined together by welding in the welding chamber.

1.3 Cold and hot extrusion:

Cold extrusion could produce parts with good surface finish, high strength due to strain hardening, improved accuracy, high rate of production. However, the process requires higher pressure and tools are subjected to higher stresses. Proper lubrication is necessary for preventing seizure of tool and workpiece. Phosphate coated billets are lubricated with soap.

Hot extrusion can be employed for higher extrusion ratios. Inhomogeneous deformation can occur due to die wall chilling of the billet. Metal may get oxidized. The oxide layer can increase friction as well as the material flow. Glass is used as lubricant for hot extrusion. Molybdenum disulfide or graphite are the solid lubricants used in hot extrusion. Canned extrusion using thin walled cans made of copper or tin is usually used for extruding highly reactive metals and metal powders.

1.4Extrusion presses:

Hydraulic presses of vertical or horizontal type are used for extrusion. Vertical presses are of capacity ranging from 3 to 20 MN. Horizontal presses occupy less space, but the billets get nonuniformly cooled. Horizontal presses upto 50 MN capacity are being used. Tubular extrusions are mostly done in vertical presses, while horizontal presses are used for bar extrusion.

Analysis of extrusion

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1. Analysis of extrusion:

1.1 Material flow in extrusion:

Extrusion pressure depends on the nature of material flow and redundant deformation during extrusion. Metal flow can be studied by etching square grid on the cross-section of one half of the billet. The billet is cut across along the length and after making the grid, the two halves are joined by brazing or simply placed together inside the die. After extrusion the two halves of the billet are separated and the grid lines are inspected for shape change. The nature of material flow pattern depends on the friction at the interface, temperature variations in the billet etc.

A frictionless condition at die-billet interface will result in homogeneous deformation, without formation of dead metal or shear zone. In case of high friction, a region of no-flow or dead metal zone forms in the corner zones. Near the die exit, shear zones are formed, especially on the periphery of the billet.Shear deformation-redundant deformation leads to enhanced extrusion load. Material flow through shear zone may result in defective extrudes. During hot extrusion, the metal near die wall gets chilled out resulting in enhancement of resistance to flow. The material at the centre flows freely. This kind of variation across the billet results in dead metal zone near wall of the die. Under high friction conditions, the shear zone may extend back into the central part of the billet. Larger dead metal zone may form due to high friction, leading to defects in extruded parts. Redundant work will be higher.

Material flow in extrusion

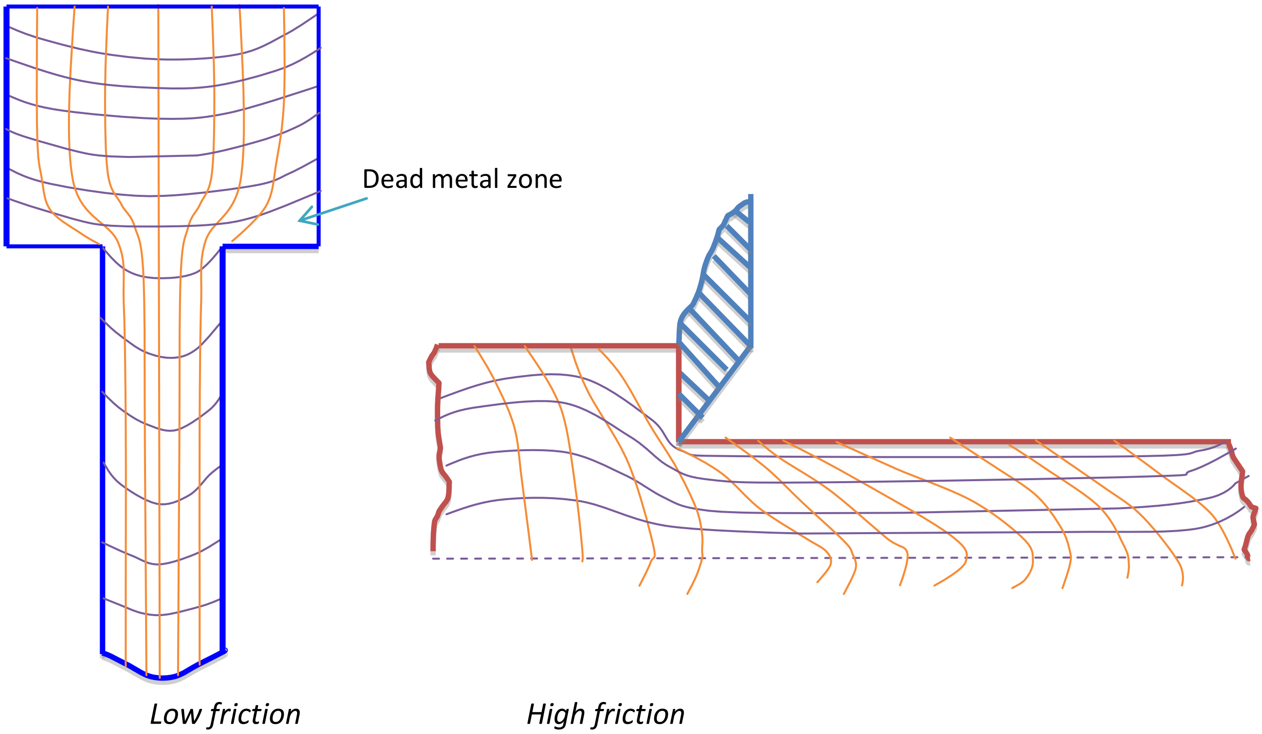

Fig. 2.1.1: Metal flow in extrusion

Redundant work refers to the work done in the redundant shear deformation due to friction. As friction increases, metal flow becomes highly non-homogeneous, enhancing the shear deformation.

1.2 Extrusion pressure for ideal extrusion:

Consider a cylindrical billet of initial diameter d_o, length l_o, being subjected to axisymmetric extrusion without friction and redundant deformation. Let the final diameter be d_f.

The ideal plastic work done per unit volume is given by:

w = $\int \sigma d\varepsilon$ --------2.1

Assuming that the stress is equal to average flow stress of the material in compression, we can write,

w = $\widetilde{Y}' \int d\varepsilon$ = $\bar{Y}'\varepsilon$ -----------------2.2

We consider the average flow stress here because the material undergoes strain hardening during extrusion. Therefore its flow stress increases from entrance to exit.

We know that $\bar{Y}'$ = $k\,\frac{\varepsilon^n}{1+n}$

And the strain during extrusion is given as:

ε= ln(A_o/A_f), because, $A_oL_o = A_fL_f$ for constancy of volume

Extrusion ratio R is defined as R = A_o/A_f

Therefore, w = $\bar{Y}'$lnR

The total work done during extrusion is given by:

wXVolume = AL$\bar{Y}'$lnR -----------2.3

Also we can write work done = Pressure X Area X Displacement = pAL

From the above expressions for work, we get the extrusion pressure as:

p = $\bar{Y}'$lnR ---------2.4

If redundant work due to friction is assumed, the extrusion pressure is expected to be higher than that predicted by equation 4.

Extrusion force = F = pAo = p$\frac{\pi}{4}d_o^2$

We define the extrusion efficiency as the ratio of ideal work of deformation to actual work of deformation.

$\eta = \frac{w_{ideal}}{w_{actual}}$and $w_{actual} = w_{ideal} + w_{friction} + w_{redundant}$

Or, p_{actual} = $\bar{Y}'$lnR/η ---------2.5

Where $\eta$is the extrusion efficiency.

If one has to consider the friction between the container and the billet alone, then the total extrusion pressure can be taken to be the sum of the die pressure and the pressure required to overcome friction in the container.

p = die pressure + friction pressure

The friction pressure is given by:

$p_f = \frac{4\tau L}{D}$,   (assuming sliding friction)

where L is length of billet in container and D is diameter of billet and τ is interface shear stress.

Note: As seen from equation 4, as the extrusion ratio increases, the extrusion force also increases.

Example: A certain material has a strength coefficient of 400 MPa and a strain hardening exponent of 0.16 . A billet of this material has a diameter of 30 mm and a length of 80 mm. This billet is extruded to a ratio of 4. Assuming square die, estimate the extrusion force required, ignoring friction. Use the following formula for extrusion pressure:

$p = \bar{Y}[(a+b\ln R)+\frac{2L}{D_o}]$, where a = 0.8, b=1.5

Solution:

R = 4 (given), $\bar{Y} = k\varepsilon^n$ = 421.64 MPa.

$\varepsilon = lnR$ = 1.39

p = 3461 MPa

Extrusion force = 2.45 MN

1.3 Direct extrusion - More accurate analysis - Slab analysis:

Slab analysis can be used for determining the extrusion pressure during direct extrusion. In order to simplify the analysis, we may assume that the die angle is small. Consider axi-symmetric extrusion. Consider an elemental cylinder of thickness dx within the deformation zone of extrusion. The radius of the cylinder reduces from R+dR to R as a result of extrusion. We can make a force balance on the cylinder, assuming that constant sliding friction exists between the billet and die wall. The semi-cone angle of the die is considered as α . Let R_o and R_f be the initial and final radii of the billet.

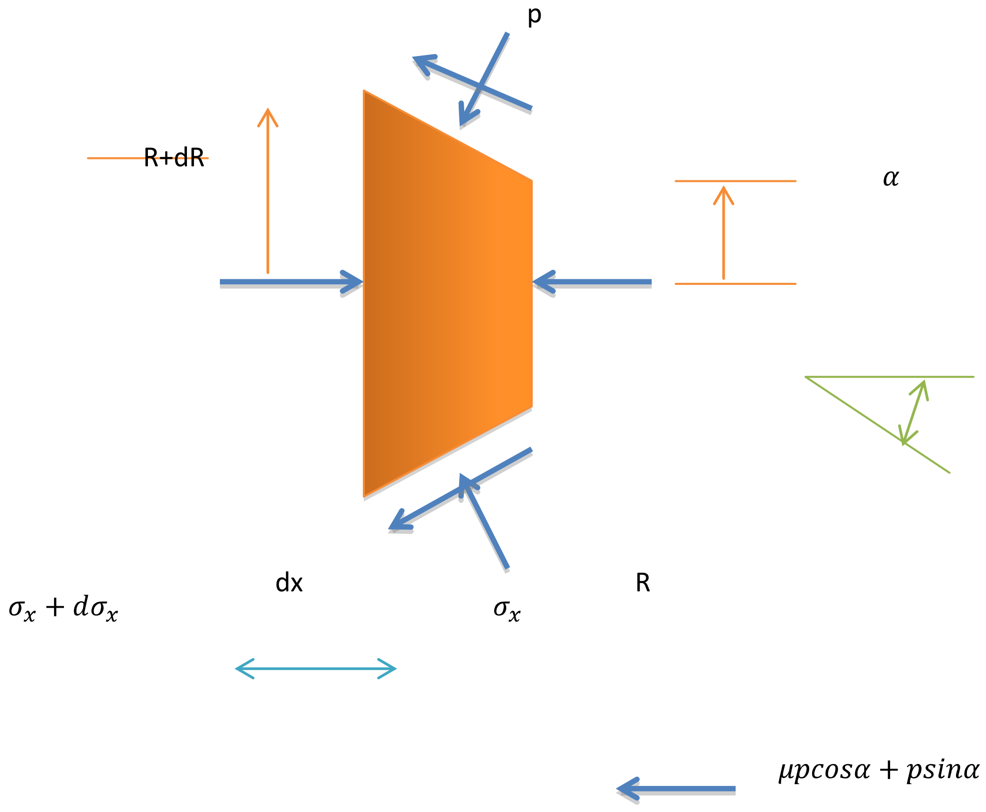

Fig.2.3.1: Stresses acting on elemental billet subjected to axi-symmetric etrusion

The slant surface area is given as:

$\frac{\pi(R+dR)^2-\pi R^2}{sin\alpha}$ = $\frac{2\pi RdR}{sin\alpha}$ (neglecting small terms) -------2.6

The force balance equation for the elemental slab along the direction of extrusion may be written as:

$(\sigma_x + d\sigma_x)\pi(R + dR)^2 - \sigma_x \pi R^2$ = $(\mu p cos\alpha + p sin\alpha)\frac{2\pi R dR}{sin\alpha}$ ---------2.7

Simplifying, neglecting the terms involving square and product of small quantities, we get

$d\sigma_x$+2$\sigma_x \frac{dR}{R}$ = $2p(1 + \mu cot\alpha)\frac{dR}{R}$ ----------------2.8

Applying the Tresca yield criterion:

Note: Treat applied stress as positive and induced stress as negative

That is: p is negative and the applied stress σ_x $will\ have\ a\ negative\ induced\ stress = -\sigma_x$

Therefore the yield criterion is written in the form:

-σ_x+p = Y → p = Y+σ_x

Substituting for p into equation 8 above, integrating we get:

$\frac{1}{B}\ln[(B)\sigma_x + (1 + B)y] = 2lnR + c$ --------------2.9

applying the boundary condition:

At R = R_f, σ_x =0 , Solving for c and simplifying, we get:

σ_x= Y$[\frac{1+B}{B}][(\frac{R}{R_f})^{2B} - 1]$ -----------------2.10

where, B = μcotα, Y is yield strength of material in compression., σ_x is extrusion pressure.

Equation 10 gives the extrusion pressure at any location x along the deformation zone.

The punch pressure to be applied can be obtained by substituting R = R_i in equation 10

And also noting that the punch pressure = -σ_x

i.ep_{ext} = Y$[\frac{1+B}{B}][1 - \left(\frac{R_o}{R_f}\right)^{2B}]$ ----------2.11

Extrusion force at punch now becomes: F = $A_o p_{ext}$

1.4 Effect of redundant deformations on extrusion force:

Due to non-homogeneous deformation as a result of friction, material undergoes shear at entry and exit sections of the die. Shear deformation consumes some energy. The work to be spent on the shear is known as redundant work.

It can be shown that the stress due to shear at entry, $\sigma_{si} = \frac{2}{3\sqrt{3}}\alpha Y$ ------2.12

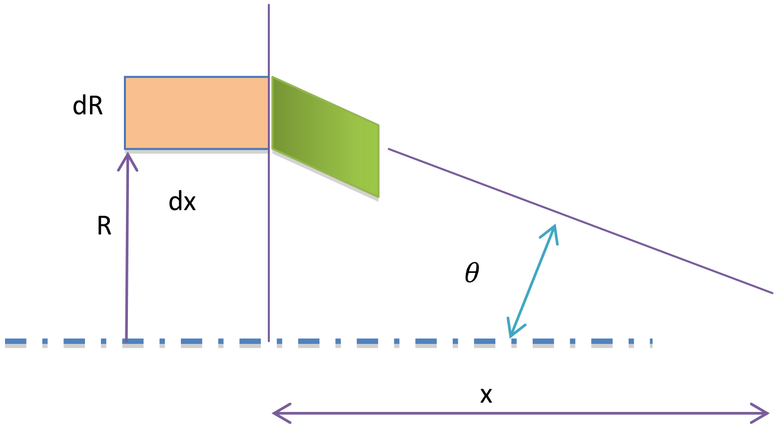

Fig. 2.4.1: Redundant shear of an element of thickness dx during extrusion

Consider a small ring element of length dx at a radius of R, with thickness dR, located at

X from the reference point.

This element gets sheared through an angle of theta as shown above.

Let the yield strength of the material in shear be $\frac{Y}{\sqrt{3}}$ = Y'(From Von-Mises criterion)----2.13

The volume of the small element is = 2πRdRdx -------2.14

Shear strain undergone by the element = tanθ = R/x ----2.15

Shear Work done on the elemental ring = dW = shear stress X shear strain

dW = Y'2πRdRdxR/x ---------2.16

Total work done on many such elemental rings can be written as:

W = $\int_0^{R_0} 2\pi R dR dx R/x$ = Y'(dx/x)$\frac{2}{3}\pi R^3$ -------------------2.2.17

We know the total volume of the ring of thickness dx = $\pi R^2 dx$

Work done per unit volume now becomes:

w = $\frac{2}{3}$Y'$\frac{R}{x}$ --------18

We can write tanα = R/x $\approx \alpha$

Therefore, shear stress at entry now becomes:

σ_{si} = $\frac{2}{3\sqrt{3}}\alpha Y$ This is same as equation 2.12.

Similarly we can obtain shear stress at exit of the conical section of the die as:

σ_{se} = $\frac{2}{3\sqrt{3}}\alpha Y$ (If no work hardening happens) -----2.19

Another approximate expression for extrusion can be written assuming that sticking friction exists at billet-die interface and that the material flows at 45 degrees.

P_{ext} = Y[1.75lnR+2L/D_o] ---------2.20

It can be noted from the above expression that as ram travel increases, L gets reduced and hence extrusion pressure.

The actual extrusion punch pressure is a function of friction, shear etc.

Therefore, a general expression for extrusion pressure can be written of the form:

P_{ext}= Y(a+blnR) ---------2.21

Value of a = 0.5 and b = 1.2 to 1.5

Example: For an alloy of aluminium the flow stress at atemperature of 420^o C is given by the expression: $\sigma = C\dot{\varepsilon}^m$ where C = 200 MPa and m = 0.11. This alloy is hot extruded from an initial diameter of 180 mm to a final diameter of 60 mm. Length of billet is 400 mm. The speed of extrusion is 60 mm/s. Assuming square die and poor lubrication determine the extrusion force. Consider the friction in the container also.

Solution:

Assuming the semi-die angle as 45^o

Extrusion pressure can be found from the expression:

p_{ext} = $Y[\frac{1+B}{B}][1-\left(\frac{R_o}{R_f}\right)^{2B}]$

B = $\mu cot\alpha$ = 0.15

Assuming μ=0.15

R = 9

Average Strain rate can be calculated from:

$6vlnR/D_o$ = 4.39

Y = 235.34 MPa

p = 703.67 MPa

Friction pressure in container = 4kL/Do (Assuming sticking friction)

K = Y/$\sqrt{3}$ = 235.34/1.732 = 135.87

Pf = 1207 MPa

Extrusion force = 48.6 MN

Further analysis and extrusion defects

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1.Further analysis and extrusion defects:

1.1 Strain rate in hot extrusion:

Strain effects on flow stress and hence on extrusion pressure are predominant for hot extrusion (due to strain rate sensitivity). Therefore, it is rather difficult to predict extrusion force in hot extrusion. We can estimate the strain rate at any location x in the billet from the geometrical considerations.

Let a cylindrical billet has initial radius of Ro and extruded radius of Rf. α be semi-cone angle of the die.

We can write the strain rate at any location x from entry of die as:

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = -2\frac{V_O R_O^2}{(R_O - x\tan\alpha)^3}\tan\alpha \text{ ------------3.1}$$

The average strain rate undergone by a billet is given by:

$$\bar{\dot{\varepsilon}} = \frac{6V_O D_O^2 \tan\alpha}{(D_0^3 - D_f^3)} \ln R \text{ -------3.2}$$

V_o is velocity of ram

We can say that for hot extrusion, the extrusion pressure,

p is directly proportional to stain rate. As strain rate increases, the extrusion pressure also increases, almost linearly. As ram speed increases, the extrusion pressure also increases, due to increasing strain rate. However, the extrusion pressure is reduced with increased working temperature in hot extrusion.

Further, with higher ram speeds, adiabatic conditions prevail, the billet does not cool fast enough, causing increase in temperatures rapid enough to cause localized melting. Cracks may initiate due to this. Hot shortness also can cause cracking. Such cracks are called speed cracks, as they are caused by high ram speeds.

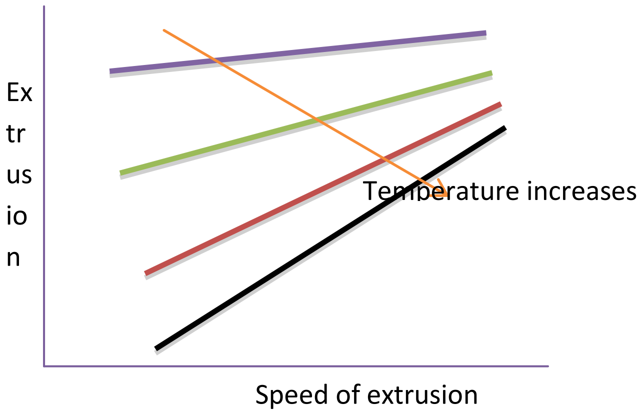


Fig. 1.1.1: Effects of temperature and velocity on extrusion force

A general expression for extrusion pressure in hot extrusion is usually given in the form:

P = klnR, where k is a factor depends on other factors during hot extrusion.

Optimum extrusion die angle:

We have seen in previous lecture that for ideal, frictionless extrusion, the extrusion pressure is given by:

p = Y lnR, which indicates that the extrusion pressure is independent of the die angle.

However, during extrusion, there is friction, which in turn increases the extrusion pressure.

There is redundant deformation which also demands some work or energy. We have seen that the extrusion force with friction depends on length of contact between die and billet. See equation 20.

Variation of extrusion pressure or force with die angle is shown.

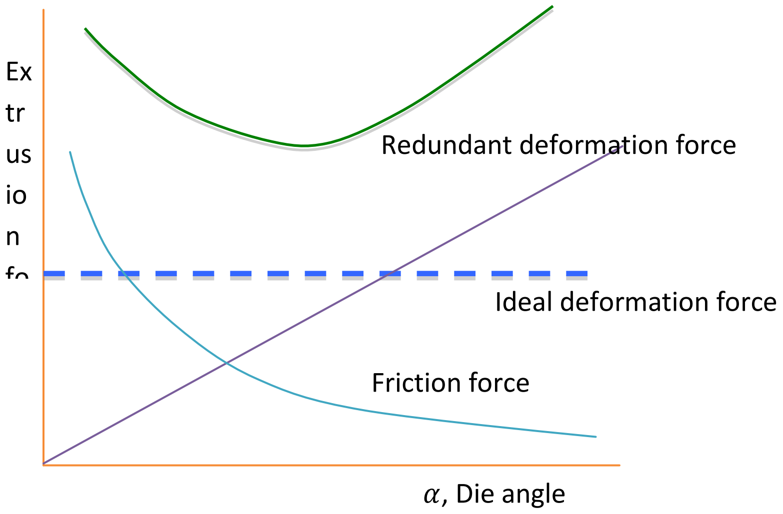


Fig. 1.1.2: Variation of various forces during extrusion with die angle

As seen from the graph, the force required to overcome friction increases with decrease in die angle. This is because, with reduced die angle, length of contact increases. Thus extrusion force increases. See eqn. 20.

On the other hand we observe that the force needed for redundant shear deformation increases with increase in die angle. This is because as the die angle is increased, there is more shear of the material, hence more redundant deformation.

The total extrusion force is a minimum at a particular die angle. This angle is called optimum die angle.

The area reduction r is defined as:

$r = (Ao-Af)/Ao = 1-Af/Ao \rightarrow \quad R = 1/(1-r)$

In extrusion, the extrusion ratio and also reduction r increase with increase in die angle. Reductions of 8 are commonly used in extrusion. That is, R = 8 and hence r = 0.875.

Example: Low carbon steel billet of initial diameter of 60 mm and length of 150 mm is extruded at 1400 K using a square die at a speed of 130 mm/s. Estimate the extrusion force for extruding the billet to a final diameter of 40 mm. Assume suitable data and assume poor lubrication.

Solution:

We can employ the expression: p = $\overline{Y}$(a+blnR) for estimating extrusion pressure.

The constants a and b are: a=0.8, b=1.5

In hot working the flow stress is strain rate dependent.

We can assume the flow stress as: $\sigma = C\dot{\varepsilon}^m = \overline{Y}$

For low carbon steel, C = 100 MPa and m = 0.1 (Average values)

R = Ao/Af = $(Do/Df)^2$ = 3600/1600 = 2.25

Strain rate is calculated using equation 23: $\dot{\bar{\varepsilon}} = \frac{6V_o D_o^2 tan\alpha}{(D_0^3 - D_f^3)}$lnR= 14.99 s^{-1}

Assume square die, that is, α=45 degrees

$\overline{Y}$ = 131.09 MPa

p = 264.33 MPa

Extrusion force = p X Area = 0.75 MN

1.2 Extrusion die:

Die and punch for extrusion are subjected to severe conditions of stress. Extrusion die are made from die steel or high carbon high chromium steels. The die is supported in a die holder and bolster. All these constitute the die head. The container has a liner shrunk into a thick shell in order to withstand high pressures. The extrusion ram has a follower pad in front so as to protect it from the hot billet. Usually, extrusion dies are conical in shape. Too small a die angle will increase friction and too large an angle will increase the friction force. The optimum semi-die angle for extrusion is usually in the range 45 to 60°. Square dies, with 90o angle can be used for aluminium, as it has low flow stress. Special wear resistant coatings can be applied on die surface for enhancing the life of the die.

3.3 Defects in extrusion products:

Defects in extruded products occur predominantly due to friction and non-homogeneous material flow. Further, temperature variations across the billet during hot extrusion can also lead to inhomogeneous deformation. Three types of defects are prominent in extrusion. They are: extrusion defect, surface cracks and internal cracks.

Extrusion defect is basically due to inhomogeneous deformation. Material at the centre of the billet comes across least resistance compared to the material near the die wall. As a result, rapid flow happens at center. After one third of the billet is extruded, the material from periphery gets entrained towards the center and flows rapidly . Oxides present in peripheral layers are also entrained. Oxides form internal stringers near the center. This defect is known as pipe or tail pipe or extrusion defect. Die wall chilling of the outer layers of material also leads to inhomogeneous deformation. Outer layers of material cools rapidly and hence resistance to flow is higher. By reducing the friction and temperature variation between centre and periphery, this defect can be reduced. Using a dummy block smaller in diameter than the billet may form a thin film of metal and protect the billet against oxidation.

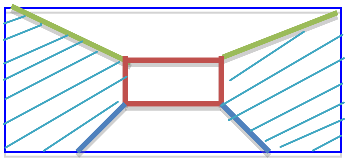
Towards the end of the process, rapid flow of material at the centre will result in pipe formation.

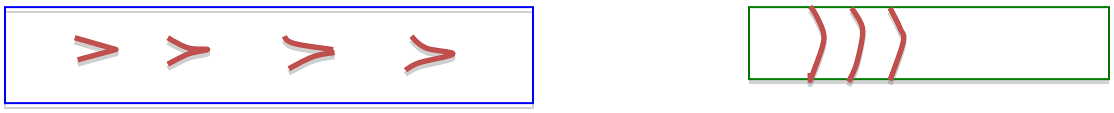
Surface cracks:

Too high extrusion speed, too large a friction too high a temperature may result in formation of surface cracks. Fir-tree cracks are transverse cracks which often occur in aluminium or magnesium due to hot shortness. Longitudinal tensile stresses may be induced on the outer layer, causing the cracks. At lower temperatures, stick-slip phenomenon may cause cracks especially in hydrostatic extrusion where pressures are very high. Sticking may happen due to thick viscous oil film.

Internal cracks:

Secondary tensile stress at the centre can cause centre cracks called chevron crack or centre burst. Such defects are known to occur under low friction conditions and low extrusion ratio. Additionally, die angle and contact length play major role in centre burst. Larger the die angle, more the inhomogeneous deformation, thereby causes chevron cracks. The ratio of height of deformation zone to length of deformation zone, h/L is very important parameter controlling this defect. Large h/L values cause secondary tensile stress at centre, because the material at centre has not reached plastic stage – due to non-homogeneous deformation. As a result, centre burst occurs. Large die angle causes larger h/L.





Chevron cracks

Fir tree cracks

Fig. 3.3.1: Extrusion defects

Temperature of extrusion plays a very vital role on soundness of the extrudes. Multiple factors are involved in selection of working temperature. Strain rate, temperature of working and deformation force are inter-related factors affecting the quality of extruded parts. The following graph illustrates this.

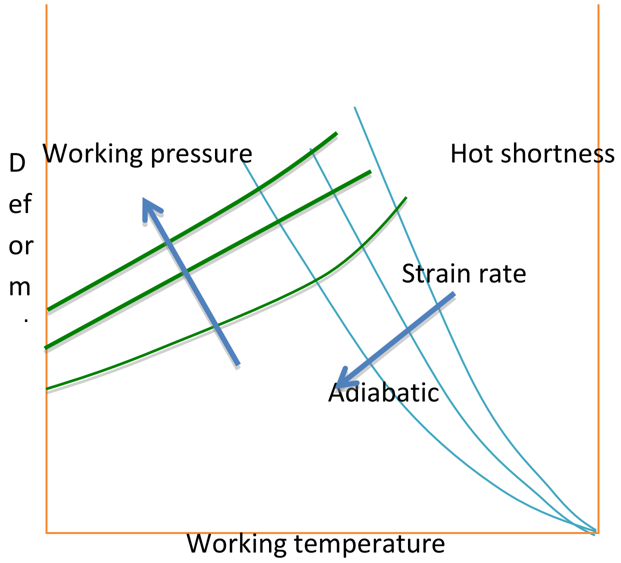


Fig. 3.3.2: Temperature and strain rate effects on deformation of material during extrusion

When working temperatures are higher, corresponding working pressures are lower. Limiting temperature is decided by hot shortness. Similarly, strain rates are limited by adiabatic conditions and retention of more heat in the billet. Excess strain rates at a particular temperature restricts the extent of deformation due to the possibility of crack formation. Or if excess strain rates are involved in the process, the working temperature has to be reduced for avoiding hot shortness. Higher deformation temperatures reduce the pressure required for a given deformation or for a given pressure, larger deformations can be achieved.

Wire and bar drawing - Basic concepts

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1.Wire and bar drawing - Basic concepts:

1.1 Wire drawing - introduction

Bar or wire drawing is a deformation process in which the work piece in the form of cylindrical bar or rod is pulled through a converging die. The stress applied is tensile. However, the material is subjected to compressive stress within the die thereby deforming plastically. A bar or rod is drawn down in order to reduce its diameter. In general, drawing results in reduction in area of cross-section. Drawn rods are used as raw materials for making bolts etc. Wire drawing is used for producing wires e.g. electrical wires, cables, strings, welding electrodes, fencing etc. Basic difference between bar drawing and wire drawing is the size of bar stock used for bar drawing is large. Wire is a drawn product having less than 5 mm. For wire drawing smaller diameter bar stock is used. Wire drawing is usually done in multiple steps, using 4 to 12 dies, because the length of the wire drawn is very large-several meters. Bar drawing is done in single draft. Draft is the difference between initial and final diameter. Wire drawing is a continuous process.

A draw bench is used for drawing of rods, bars and tubes because rods and bars can not be coiled. The rod or bar is pointed by swaging operation and fed into the drawing die. The tip of the bar is clamped into the jaws of the draw head and the drawing operation is carried out continuously. The drawhead is moved using chain drive or hydraulic power pack. Draw speeds can be as high as 1500 mm/s.
In wire drawing a series of dies are used in tandem. The drawn wire is wound on capstan between each pair of dies. Usually drawing is done cold. Maximum reduction in cross-sectional area per pass of drawing is restricted to 45%. Beyond this reduction, tensile stress may increase and surface finish may become poor. Due to large stress involved in drawing, the drawn wire gets strain hardened. Therefore, intermediate annealing is required before next stage of drawing.

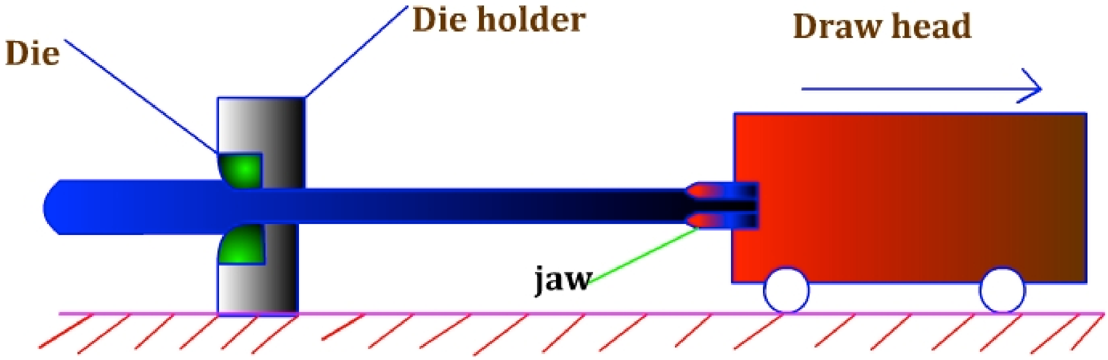


Fig.1.1.1: Wire drawing: A Draw Bench

The raw material for wire drawing is usually a hot rolled rod. The rod is coiled and fed into the die after subjected to acid pickling to remove oxides. Before drawing, the rod is lubricated. In order to retain the lubricant of the surface, oxalate or sulfate coating is given to the rod. Soap solution or oil is used as lubricant. The rod is dipped into lubricant bath before fed into the die. A bull block is used on the other end in order to wind the drawn wire. Wire drawing is completed with multiple draw head and bull blocks, with maximum reduction in each step limited to 35 to 40%. After each step of reduction, the wire diameter is reduced. Velocity of the wire and length of the wire, therefore will increase successively. This requires that the bull block be rotated at higher speeds after each reduction. A stepped cone can be used if reduction in number of blocks is to be reduced. Drawing speeds can be as high as 30 m/s.

Intermediate annealing is required before next step of drawing in order to improve the ductility of the wire. Patenting is a heat treatment process adopted for high carbon steels (musical wires) in order to obtain optimum strength and ductility. In this process the wire is dipped in molten lead bath kept at 315^{o}C. This will ensure the formation of pearlitic structure in the drawn wire, thereby improving its strength. Wet drawing involves dipping the wire inside a lubricant bath before the next stage.

1.2 Drawing die:

Die for drawing may be made of tool steel, tungsten carbide or diamond. For drawing fine wires, diamond die is used. Normally the die is made as an insert (called nib) into alloy steel casing.

The cross-section of a drawing die assembly is shown below:

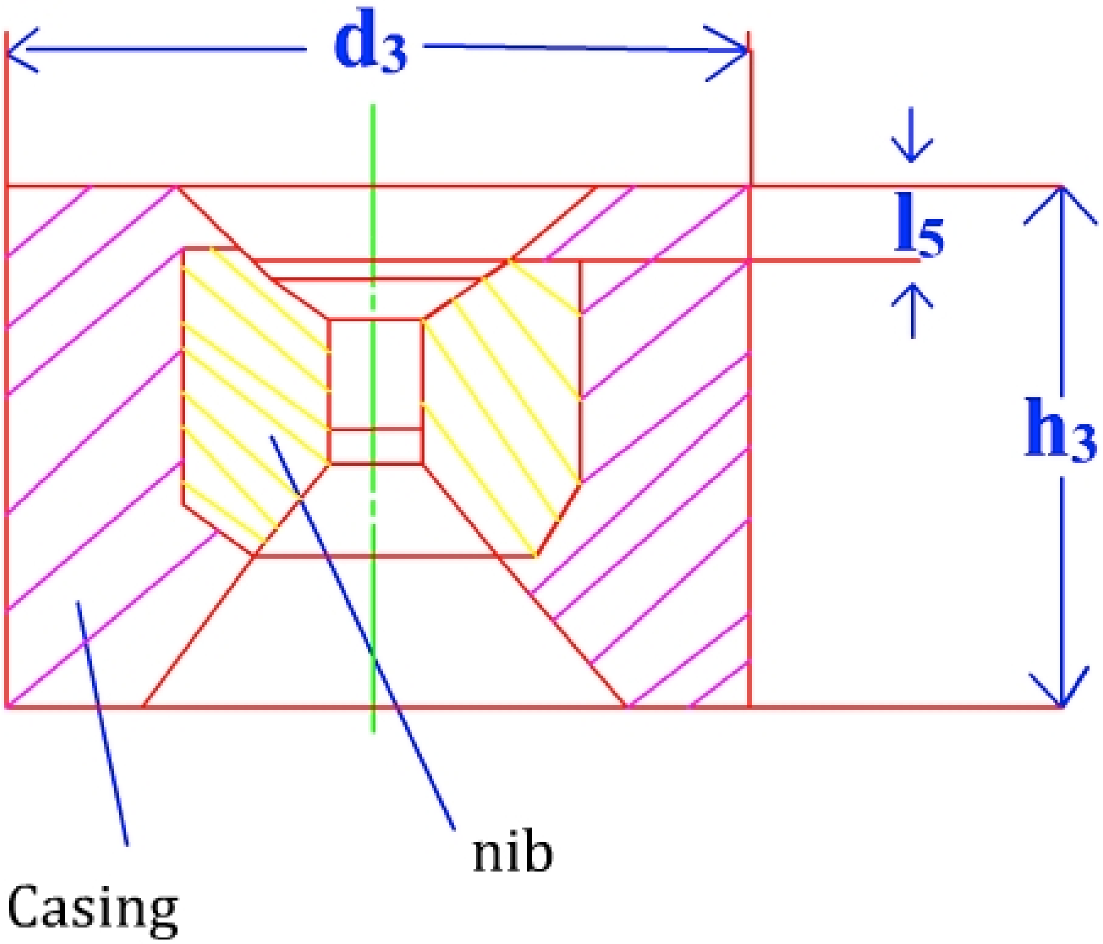


Fig.1.2.1: Cross-section of a drawing die

The entrance of the die assembly has bell assembly so as to facilitate the entry of lubricant along with the wire. Reduction in diameter takes place in approach angle section. Back relief provides space for expansion of the drawn wire. The bearing region causes frictional drag on the wire, which helps in movement of the wire inside the die. The steel casing helps hold the die.

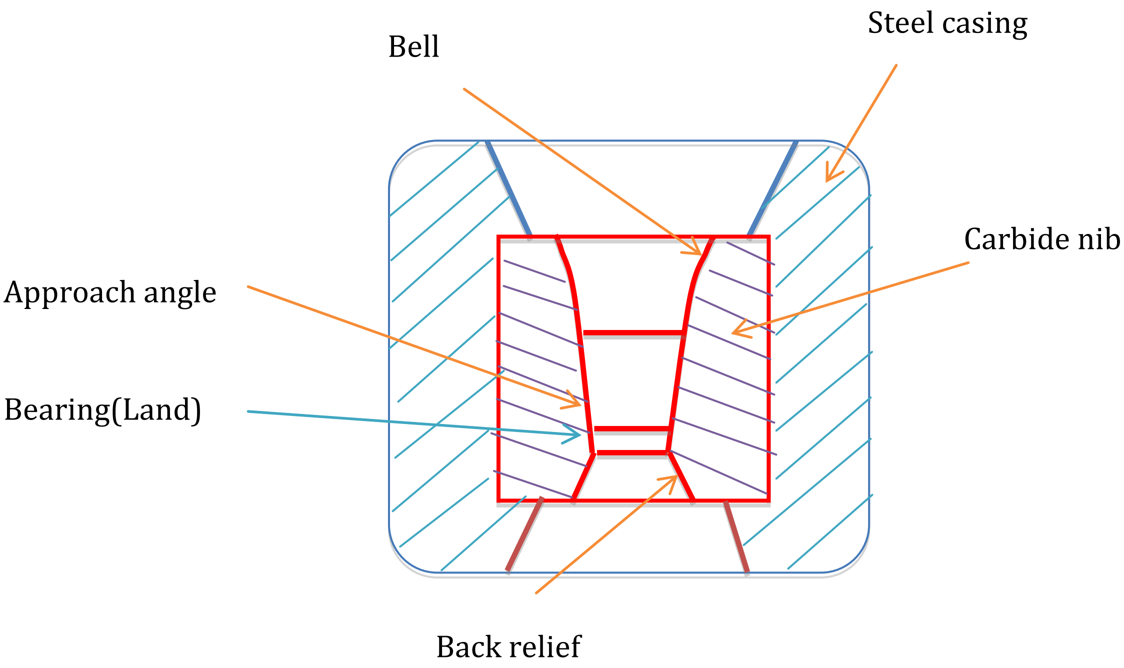


Fig. 1.2.2: Cross-section of a drawing die assembly

1.3 Typical drawing processes:

Drawing of bars could be carried out using a draw bench, as shown in figure. Hydraulically-operated or motor-driven carriages are used fro drawing the bar through the die. Multiple bars could be drawn in the draw bench, using several drawing dies on the same machine.

Drawing of wires is usually accomplished using single or multiple drafts as shown in figures below:
Continuous drawing of wires is done through a series of drawing dies, with intermediate winding drums. These drums are run by electric motors. They wind the drawn wire before feeding it to the next reduction stage. The drum applies mild tension on the wire, which is being drawn. Multiple steps of drawing, also called tandem drawing are required as the reduction of diameter achieved per pass is usually limited.

Typical wire drawing processes, using single or multiple drafts are shown schematically below:

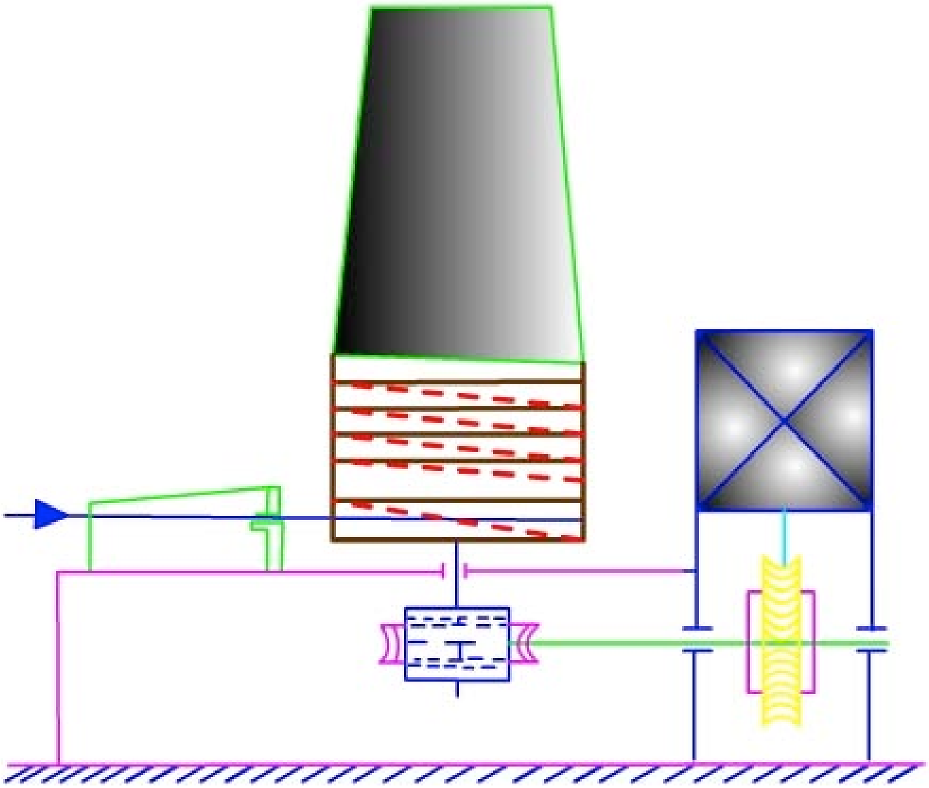


Fig. 1.3.1: Single draft drawing

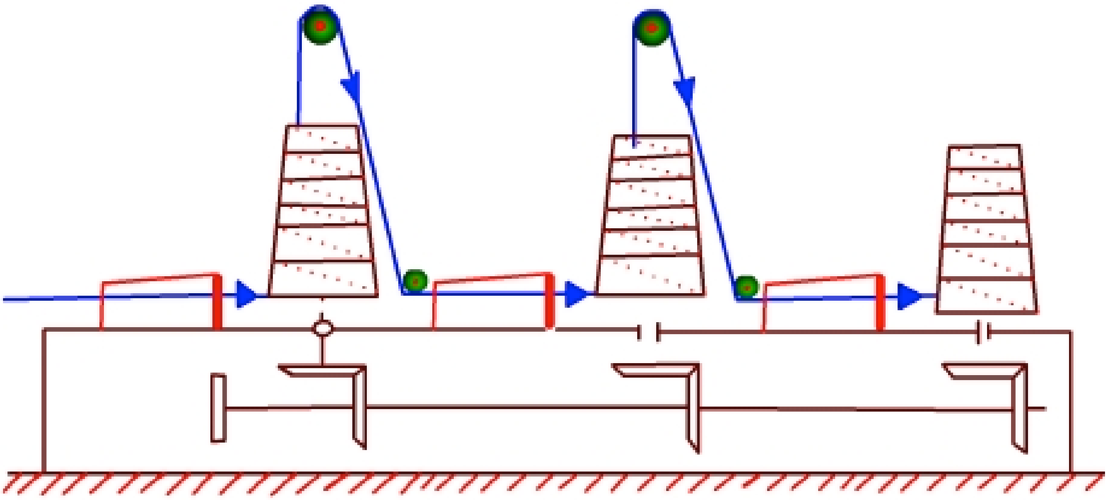
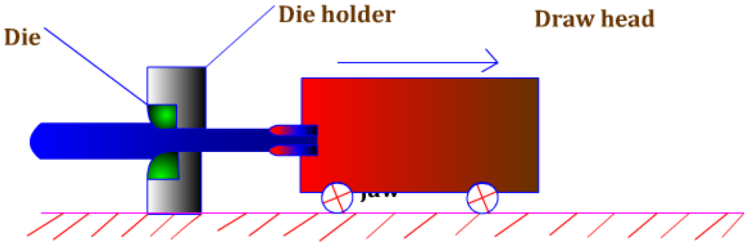


Fig. 1.3.2: Tandem Drawing

The following animation shows the process of drawing of bars using a draw bench: rcm_10_7.swf

Note :Can be viewd only by Acrobat 9.0 and above


Die
Die holder
Draw head
jaw

Bar, Wire and tube drawing

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1.Analysis of wire drawing:

1.1 Analysis of wire drawing

Consider the drawing of a wire through a conical shaped draw die, as shown below, schematically:

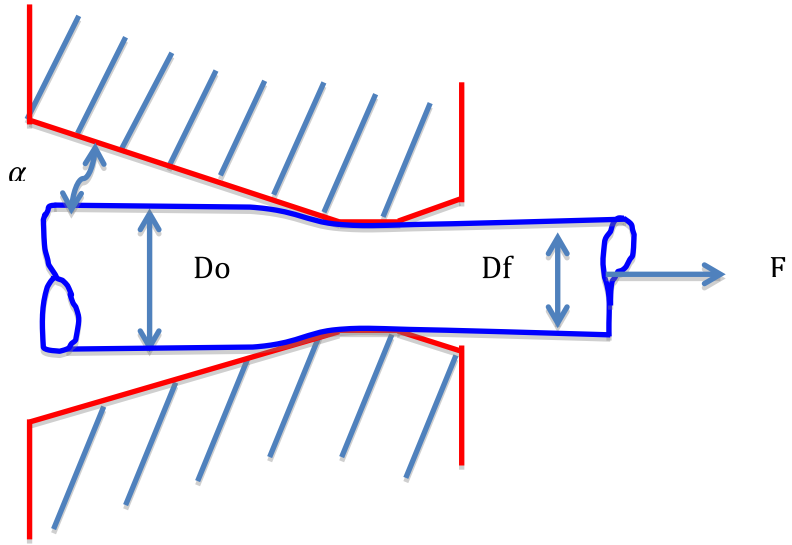

Fig. 1.1.1: Schematic of wire drawing process

Some of the important terms associated with wire drawing are to be understood first. They are:

Area reduction r is defined as (Ao-Af)/Ao -----2.1

The drawing ratio R is defined as Ao/Af = 1/(1-r) ------------2.2

The important parameters which affect the wire drawing force are the drawing ratio, die angle, material flow stress, friction etc.

Approximate expression for drawing force can be written based on plastic work or strain energy. Ignoring friction and redundant work we can write the draw pressure as:

Draw pressure p = $\bar{Y}\ln(\frac{A_0}{A_f}) = \bar{Y}\ln R = \bar{Y}\ln(\frac{1}{1-r})$ ----------------2.3

The draw pressure is dependent on draw ratio R. As draw ratio is increased the draw pressure increases.

$\bar{Y}$is the average flow stress of the material.

1.2 Analysis of wire drawing with friction:

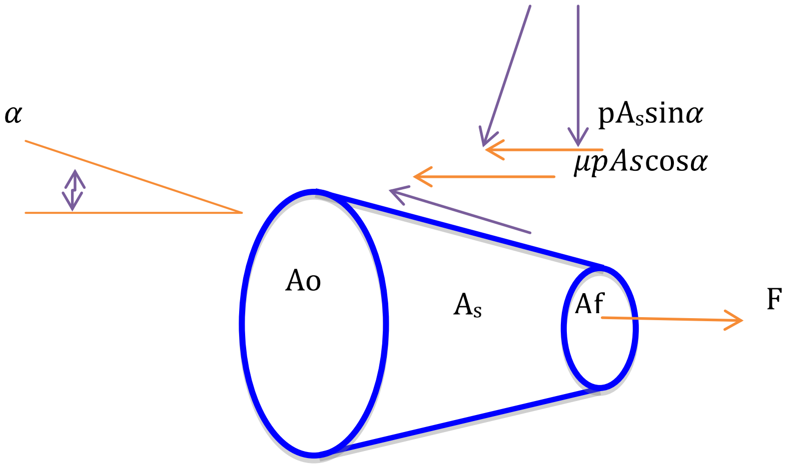

Fig. 1.2.1: Stresses acting on elemental section of the drawn wire during drawing

Consider a conical element of the workpiece inside the die. The surface area of the element is taken to be As. Let α be the semi-cone angle of the die.A_o is the cross sectional area of the work piece at entry of the die. A_f is the exit cross-section area. We can write the surface area of the element $A_s$as:

$A_s = \frac{A_o - A_f}{sin\alpha}$ ---------------2.4

The forces acting on the elemental work piece are:

Force due to normal die pressure = pAs sinα

frictional force = $\mu pAs\ cos\alpha$

Draw force = F,

Making force balance on the element:

$pA_s sin\alpha + \mu pAs\ cos\alpha = F$ --------2.5

Substituting for A_s from 4, we get:

$p(A_o - A_f) + \mu p(A_o - A_f)\cot\alpha = F$

$F = (A_o - A_f)p\ [1+\mu\cot\alpha)$ ---------2.6

We can eliminate p from the above equation by considering a frictionless drawing. In the absence of friction:

Draw force = $F = (A_o - A_f)p = \bar{Y}'\ln(\frac{A_0}{A_f})Ao$

From this, we can write: $p = \frac{Ao}{Ao-Af}\bar{Y}'\ln(\frac{Ao}{Af})$ -------2.7

Substituting 7 in 6, we get:

$F = A_o\bar{Y}'\ln(\frac{Ao}{Af})(1+\mu cot\alpha)$ ------------2.8

Or, the draw stress with friction can be written as:

$p = \bar{Y}'\ln(\frac{Ao}{Af})(1+\mu cot\alpha)$ -------------2.9

As seen from the above equation, the draw stress depends on the die angle. Higher the die angle, higher the draw stress.

A simple equation proposed by Schey can also be used for the draw stress. It is given as:

$\sigma_d = \bar{Y}'(1+\frac{\mu}{tan\alpha})\theta\ln(\frac{A_0}{A_f})$ ----------2.9A

where $\theta = 0.88 + 1.2\frac{D}{L_c}$. which accounts for redundant deformation. It is called inhomogeneity factor.

D is average diameter of the billet, L_c is contact length of the wire in the die.

$L_c = \frac{Do-Df}{2sin\alpha}$ and $D = \frac{D0+Df}{2}$

We can determine the draw force from 2.9A as:

F = $A_f\sigma_d$

1.3 Strip drawing – slab analysis:

Strip drawing is a process of drawing in which, metal of large thickness gets reduced in thickness and increase in length through a converging die.

Consider a rectangular strip of initial thickness ho and uniform width. This strip is passed through a convergent die, so that its thickness gets reduced to hf. The semi-die angle is taken to be α.

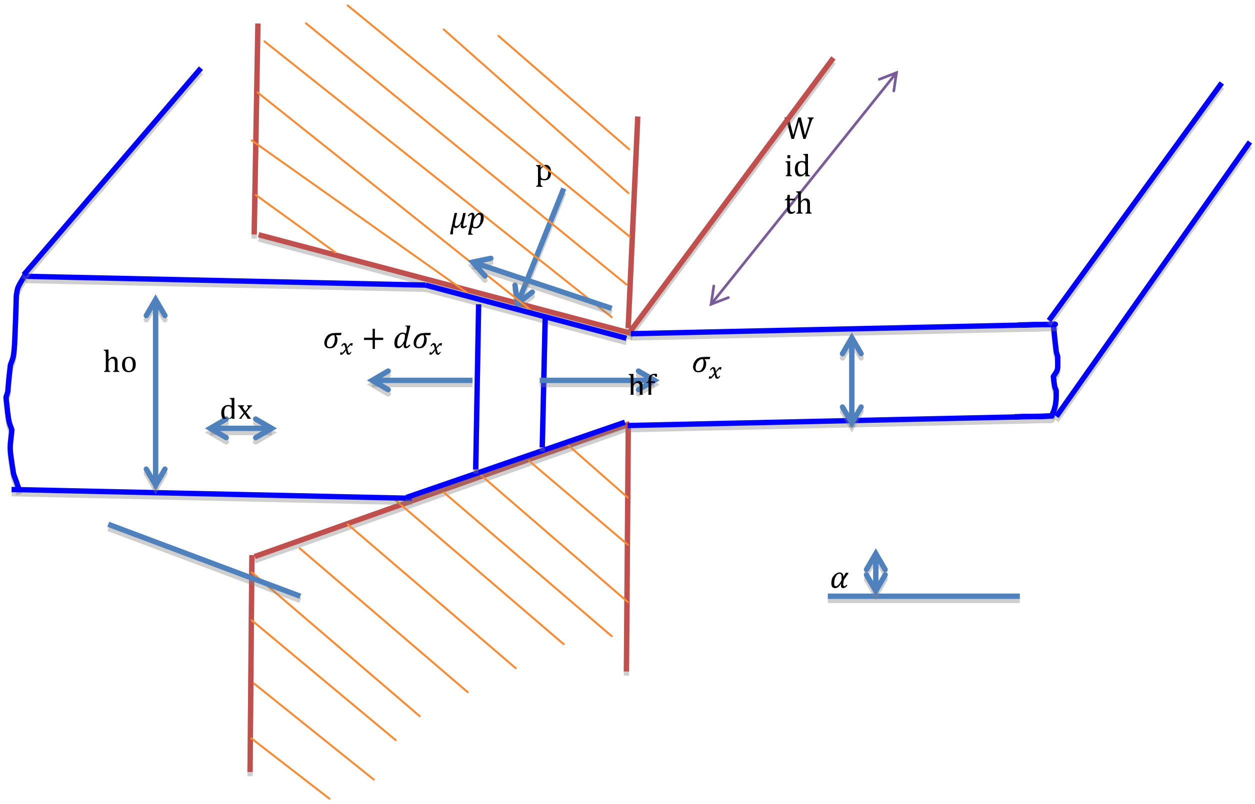

Fig. 1.3.1: Strip drawing – stresses acting

In the analysis, we may assume plane strain compression of the strip, as the width of the strip does not change during the process.

Consider a strip of thickness dx within the die. Let the strip of initial thickness h+dh be reduced in thickness to h after the deformation. We can write the force balance on the elemental strip.

The slant area of the strip = dx/cosα (Width is taken as unity)

Resolving the forces along the direction of drawing and writing the force balance,

$\sigma_x dh + h d\sigma_x + 2\mu p dx + 2 p dx tan\alpha$ = 0 -----------2.10

Dividing by dh on both sides,

$\sigma_x + \frac{h d\sigma_x}{dh} + p(1 + \mu cot\alpha)$=0 ----------------2.11

Applying Tresca yield criterion, we have

σ_x+p = $\overline{Y}'$ where $\overline{Y}'$is plane strain yield strength and is = 2Y/$\sqrt{3}$ ------2.12

p = $\overline{Y}' - \sigma_x$ ----------2.13

Substituting in 2.11, and letting B = $\mu cot\alpha$we get:

$\frac{d\sigma_x}{B\sigma_x - Y\prime(1+B)}$ = $\frac{dh}{h}$ ------2.14

Integrating and applying the boundary condition:
At h = h_o, σ_x =0

We get:

$\sigma_x = \overline{Y}\prime \frac{1+B}{B}(1 - \left[\frac{h_f}{h_o}\right]^B)$ --------2.15

By applying the same procedure, we can derive a similar expression for the draw stress of wire drawing process.

The draw stress for wire drawing process is given by:

$\sigma_x = \overline{Y}\prime \frac{1+B}{B}(1 - \left[\frac{d_f}{d_o}\right]^{2B})$ -------2.16

Example: A steel wire is drawn to 24% reduction from initial diameter of 10mm. The flow stress of the material is given by: $\sigma = 1200\varepsilon^{0.28}$MPa. The semi die angle is 6o and μ=0.1. Calculate the draw stress and the power required for the deformation if the wire moves at a speed of 2.5 m/s.

Solution:

Given: r = 0.24 = (Ao-Af)/Ao

We can calculate the strain from the expression: $\varepsilon = ln\frac{1}{1-r}$ = 0.274

The average flow stress is given by: $\overline{Y}'$= k$\frac{\varepsilon^n}{1+n}$ = 1200(0.274)$^{0.28}$ / 1.28 = 652.73 MPa

We can use equation 9 for calculating the draw stress:

p = $\overline{Y}' \ln (\frac{Ao}{Af})(1+\mu cot\alpha)$ = 349.86MPa

Now, the final area of cross-section of the wire, Af = Ao(1-r) = 59.66 sq.mm

To determine power required, we can use the formula:

Power = Draw force X speed of drawing = Draw stress X A_f X speed = 52180.93 W

Aspects of wire drawing and tube drawing

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1. Further aspects of wire drawing and tube drawing:

1.1 Redundant work:

Redundant deformation happens during wire drawing due to shear of the material in the deformation zone. A redundant work factor can be employed to account for redundant work. The redundant work factor is defined as:

$\phi = \frac{\varepsilon^*}{\varepsilon}$------3.1

Where ε^* is the increased strain of the deformed material corresponding to the yield stress. ε^*can be obtained from stress-strain curve by superimposing the flow curve of the drawn material on the annealed flow curve for the same material.

The redundant factor is related to the deformation zone geometry parameter Δ as:

$\phi = 0.8+\frac{\Delta}{4.4}$-------3.2

where the deformation zone geometry for wire drawing is given by:

$\Delta = \frac{\alpha}{r}[1+(1-r)^{1/2}]^{1/2}$ ----3.3

As seen from the above expressions, the redundant work increases as the semi-die angle is increased. Similarly, it decreases for increase in reduction r.Practically, the semi-die angles employed is in the range 6 to 10^{o}. The reductions employed commercially are in the range 20 to 25%.Δranges from 2 to 3.

One method of including the redundant work in draw force is multiplying the draw stress by redundant work factor as given below:

$$p = \phi\bar{Y}\ln\left(\frac{Ao}{Af}\right)(1+\mu cot\alpha) \quad \text{-----------3.4}$$

Another approach is similar to what has been discussed in extrusion chapter. We can determine the redundant work from the shear strain on the material both at entry and exit of the draw die. This work is then added to the draw stress obtained by the slab analysis.

$$\sigma_x = \bar{Y'}\frac{1+B}{B}\left(1-\left[\frac{d_f}{d_o}\right]^{2B}\right)+\frac{4}{3\sqrt{3}}\alpha\bar{Y'} \quad \text{-----3.5}$$

1.2 Optimum die angle:

Similar to extrusion, there exists optimum die angle for drawing process. The optimum angle is determined based on the minimum total energy required for drawing. The total energy for drawing (or work for drawing) is the sum of ideal deformation work, redundant work and frictional work.

One can also define an optimum for the deformation zone geometry as:

$$\Delta_{opt}= 4.9\left[\frac{\mu}{\ln\left(\frac{1}{1-r}\right)}\right]^{1/2} \quad \text{--------3.6}$$

1.3 Maximum reduction in drawing:

Number of drawing steps or passes required are more if larger reductions are desired. If the required reduction is attempted in a single step, the draw stress required may be too high.

If the draw stress applied reaches the material's yield strength, then instead of getting drawn, the material will start yielding. The material will start elongating locally instead of getting drawn out. Therefore, the draw stress should not be allowed to reach the yield strength of the work material. For maximum drawing, we can say that the draw stress is just equal to the material yield strength. Considering frictionless, ideal deformation without any shear, we can write for maximum drawing:

p = $\bar{Y}\ln(\frac{A_0}{A_f}) = \bar{Y}$ -------3.7

Or, we have:

$\ln[\frac{A_0}{A_f}] = 1$

Or

$(A_o/A_f)_{max} = 2.718$

From which we get

$r_{max} = 0.632$ ------------3.8

The above analysis is based on the assumption that friction is absent and there are no redundant work and there is no work hardening during drawing.

If work hardening and friction are considered, the limiting reduction will be less than 63%.

1.4 Die pressure:

Applying the yield criterion for wire drawing, at any location within the deformation zone, we can write:

p = Y - σ_x, where Y is yield strength at the location considered and σ_x is the tensile stress at the location.

As we see from this equation, the draw stress = σ_x at exit.

i.e. $\sigma_d = Y - p$

Towards the die exit, the yield strength increases due to work hardening. Therefore, draw stress increases towards the exit, as shown in figure. Due to this reason the die pressure p decreases towards the die exit.

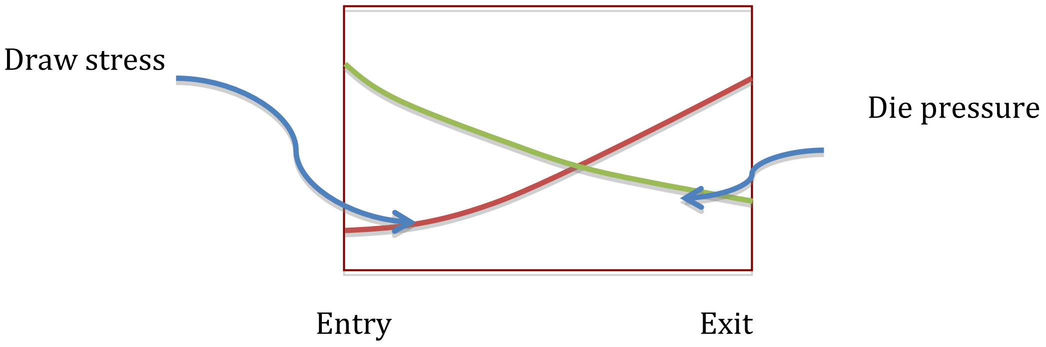

Fig. 1.4.1: Variation of die pressure and draw stress during drawing process

1.5 Tube drawing:

Tube drawing is a tube finishing process carried out on the tubes made through the other methods like Mannesmann mill. Tube sinking is done without using a mandrel, to reduce the diameter of the tube without affecting the thickness.

Tube drawing is used to reduce thickness and diameter using mandrels.

Mandrel or plug may be cylindrical or conical in shape. Using a plug ensures uniform thickness. The mandrel may be kept stationary or moved along with the tube.

Floating mandrel are used where the length of the tubes are long. Drawing forces involved in tube drawing with plug are always higher. With moving mandrel, there is a forward frictional drag which pulls the metal into the die, at the entry.

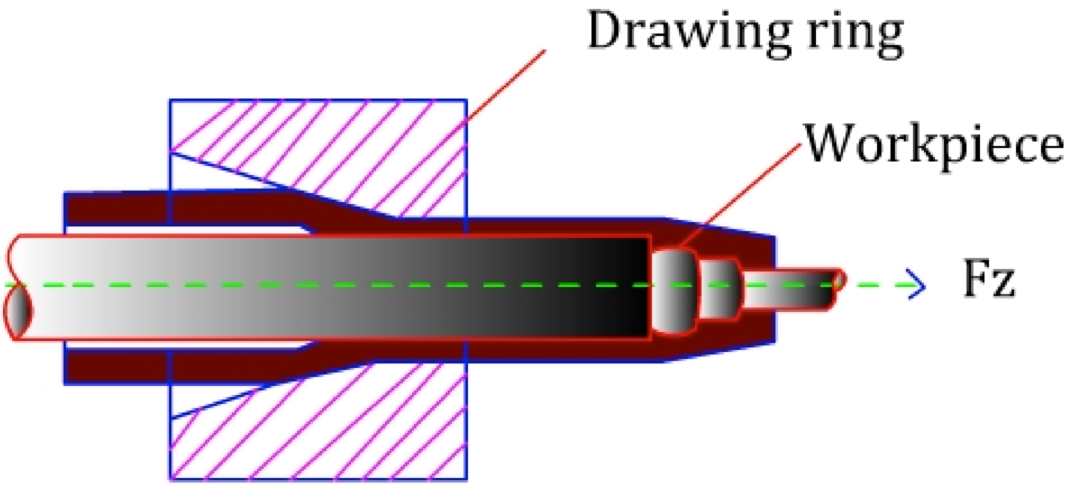

Fig.1.5.1: Tube drawing with mandrel

Draw stress for tube drawing with fixed plug is given by:

$\sigma = \bar{Y}' \frac{1+B}{B} [1 - \left(\frac{h_f}{h_o}\right)^B]$ ---------3.9

where B = $\frac{\mu_1+\mu_2}{tan\alpha - tan\beta}$

h is tube wall thickness.

α is angle of the die and $\beta$is the angle of mandrel.

For moving mandrel, B = $\frac{\mu_1-\mu_2}{tan\alpha - tan\beta}$

Because the friction at die tube interface acts against the direction of drawing while at tube – mandrel interface friction acts so as to drag the tube towards the exit.

For tube sinking the draw stress is given by:

$\sigma = \bar{Y}' \frac{1+B}{B} [1 - \left(\frac{A_f}{A_o}\right)^B]$ --------3.10

1.6 Strain rate in hot drawing:

Similar to hot extrusion, the average strain rate during hot drawing can be written as:

$\bar{\varepsilon} = \frac{6V_o}{D_o} \ln\left(\frac{Af}{Ao}\right)$ -------3.11

The average flow stress can be determined from the stress-strain rate relation for the work material.

1.7 Drawing defects:

Center cracks can occur in drawn products due to larger die angle, lower reduction per pass, friction etc.

Longitudinal cracks or folds occur on surface of the drawn wire which may open out during the use of the drawn product.

Residual stresses are induced in drawn bars or wires during cold drawing. If the reductions are low, the surface of the drawn part is subjected to compressive residual stress. Compressive residual stress on surface improves the fatigue life and corrosion resistance of the product.

For larger reductions, surface stress is tensile while the center has compressive residual stress. Increase in die angle increases the surface tensile stress. For reductions between 20 and 35%, highest surface tensile residual stresses are reported.

Example: Derive an expression for the maximum reduction during the drawing of a wire, which is made of a strain hardenable material.

Solution: We can write the flow stress for strain hardenable material as

$$\sigma = k\varepsilon^n$$

Assuming frictionless drawing, the draw stress is given by: $\bar{Y}\varepsilon$

Where $\bar{Y}$is average flow stress and = $\frac{k\varepsilon^n}{1+n}$

Equating draw stress to the yield strength of the material:

$\frac{k\varepsilon^n}{1+n}\varepsilon$=k$\varepsilon^n$

Or, $\varepsilon = 1 + n$ = ln(Ao/Af)

We can write reduction r = (A0-Af)/A0

Or Ao/Af = 1/(1-r)

Therefore, maximum reduction = r_{max} = 1-exp$^{-(1+n)}$

Note: If we substitute n = 0, above we get r_{max} = 0.632, which was proved earlier in the lecture.

Sheet metal operations - Cutting and related processes

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1.Cutting and related processes:

1.1 Introduction:

Sheet metal forming, also called stamping, involves operations such as cutting, drawing, spinning etc on sheets. Sheet metal forming involves predominantly tensile forces, compared to bulk forming, which involve compressive forces. Due to tensile stress, sheets may undergo localized deformation followed by cracking. Sheets are rolled products, which have thickness less than 6mm. Sheet metal operations involve work pieces with large surface area to thickness ratio. Blanks are cut from sheets. These blanks are subsequently subjected to one or more sheet forming operations in order to get the finished component. Sheet metal forming is widely used for producing wide range of products starting from household vessels to aerospace parts, to automobile or aircraft bodies. Final shape is obtained by applying tensile, shear or combination of forces and stretching or shrinking the sheet metal blanks.
Hydraulic or mechanical presses called stamping presses are used for the forming process. Die – punch combination is used for the process to impart the desired shape to the blank. Dies may be simple or compound, which include several operations. Transfer dies can be used in heavy operations.

The prominent type of force in sheet forming is tensile. In some operations shear is also used. However, reduction in sheet thickness is avoided in sheet forming, due to localized deformation called necking. Yielding, elongation, anisotropy, and wrinkling are important parameters in sheet forming. Material grain size also influences the characteristics of the formed product.

During tensile elongation of ductile material, beyond the ultimate tensile strength, localized necking begins. At the ultimate point where necking or instability is about to begin, we know that the strain is equal to the strain hardening exponent. Higher the strain hardening exponent for a metal, higher the stress it can withstand before necking. In isotropic materials, necking is usually found to occur at an angle of 55 degrees with reference to the tensile axis.
Larger strain rate sensitivity parameter leads to diffuse necking (uniform) rather than localized. This means larger amounts of uniform elongation occurs before fracture of the sheet metal.

The phenomenon of yield point in some materials such as low carbon steels produces Lueder bands. Such bands also called stretcher strains produce undesirable elongated marks on the sheet metal. Temper rolling or skin rolling could be used for eliminating these marks. Anisotropy – both normal and plastic anisotropy due to processing of sheet metals has notable influence on the forming. Coarse grain structure results in rough surface on the formed sheets. This is called orange peel effect. Residual stresses due to non-uniform deformation, wrinkling due to compressive stress are also important issues in sheet metal forming. In the following sections we discuss the various sheet metal operations.

1.2 Shearing, blanking, punching:

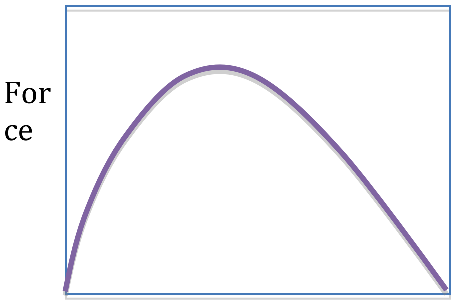
1.2.1 Shearing:

Shearing is the process of cutting off of sheets using a die and punch, applying shear stress along the thickness of the sheet. A die and punch or a pair of blades are used in shearing. Shearing happens by severe plastic deformation locally followed by fracture which propagates deeper into the thickness of the blank. The clearance between the die and punch is an important parameter whichdecides the shape of the sheared edge. Large clearance leads to rounded edge. The edge has distortion and has burr. The shearing load is also higher for larger clearance. For harder materials and larger sheet thickness, larger clearances are required. Generally, clearance can vary between 2% and 8% of the sheet thickness. Usually shearing begins with formation of cracks on both sides of the blank, which propagates with application of shear force. A shiny, burnished surface forms at the sheared edge due to rubbing of the blank along the shear edge with the punch or the die wall. Shear zone width depends on the speed of punch motion. Larger speed leads to narrow shear zone, with smooth shear surface and vice-versa. A rough burr surface forms if clearance is larger. Similarly, a ductile material will have burr of larger height.

Shearing a blank involves plastic deformation due to shear stress. Therefore, the force required for shearing is theoretically equal to the shear strength of blank material. Due to friction between blank and tool, the actual force required is always greater than the shear strength. Variation of punch force during shearing process is shown below. The maximum force required on the punch for shearing can be empirically given as:

$F_{max} = 0.7\sigma_u tL$

t is blank thickness and L is the length of the sheared edge. For reducing the shearing force, the cutting edges of the punch are made at an angle. This ensures cutting of a small portion of the total length of cutting.



1.2.2 Shearing zone geometry:

Considering the shearing of a blank, we understand that the top surface of the sheet where the punch contacts the blank, a small projection called rollover forms. This region corresponds to the small depression made by the punch on the sheet. Below this, the burnished surface which is a smooth surface formed by the rubbing of the shear surface against die and punch is present. The burnished surface is located below the rollover in case of a blank. Whereas, the burnished region is located on the upper side in case of a punched sheet. In the case of a punched hole on a sheet, the fracture zone is located below the burnished zone. The burr forms below the fracture zone. Burr is a sharp edge formed at the end of the process due to elongation of the material before completely getting severed off. The depth of the deformation zone depends on the ductility of the sheet metal. If ductility is small, the depth of this zone is small. The depth of penetration of the punch into the sheet is the sum of the rollover height and burnishing zone height. The depth of rough zone increases with increase in ductility, sheet thickness or clearance. There is severe shear deformation in the fracture zone.

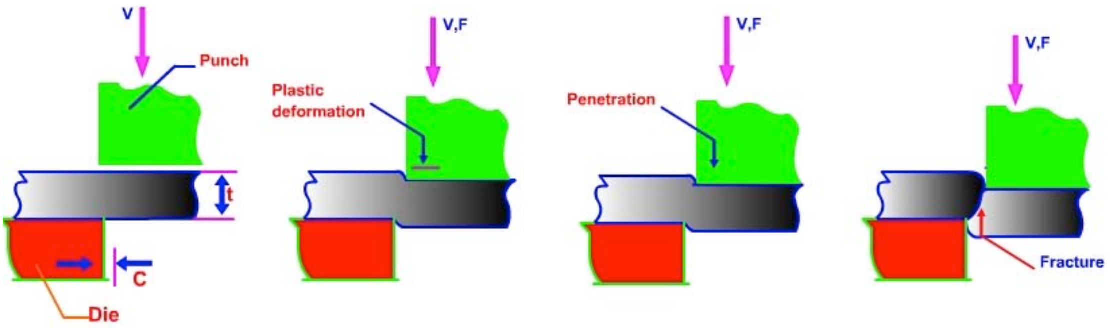


Fig. 1.2.1: Stages of shearing operation

1.3 Blanking and punching:

It is a kind of shearing operation, carried out along a closed contour. The desirable part in this operation is the metal inside the sheared contour, called blank. Example is making circular blanks out of sheets for subsequent deep drawing of cups.

Punching is the operation in which the desired part is the sheet left out after making a punch hole or contour shearing.

Die-punch clearance is very critical for blanking and punching, as it governs the kind of finish obtained on the final part. Typical recommended clearances for the operations are given in table below:

Table 1.3.1: Radial clearances for blanking and punching:

Material	Radial clearance as percentage of thickness		
	High precision	Good finish	General
Aluminium	1	4-6	10-12
Low carbon steel	1-2	5-7	9-11
Stainless steel	1-2	4-5	10-12
Brass	1	2-5	7-10

Punch diameter has to be smaller than the die hole. The clearance between die and punch is based on the type of process.

For blanking operation for obtaining a blank of diameter Db the clearance is given on the punch.Diameters of punch and die are given by:

Dia of punch = Db-2c and die diameter = Db, where c is radial clearance.

For punching operation on a sheet with a hole of diameter Dh,
the die hole diameter = Dh+2c
the punch diameter = Dh

In general, the clearance can be expressed as:
c = At, where A is clearance allowance and t is sheet thickness.
The clearance allowance A is taken to be 0.075 for most of the steels and 0.045 for aluminium alloys.

For easy removal of slug during punching or blanking, a small angular clearance of 1 degree to 1.5 degree is provided in the die hole.

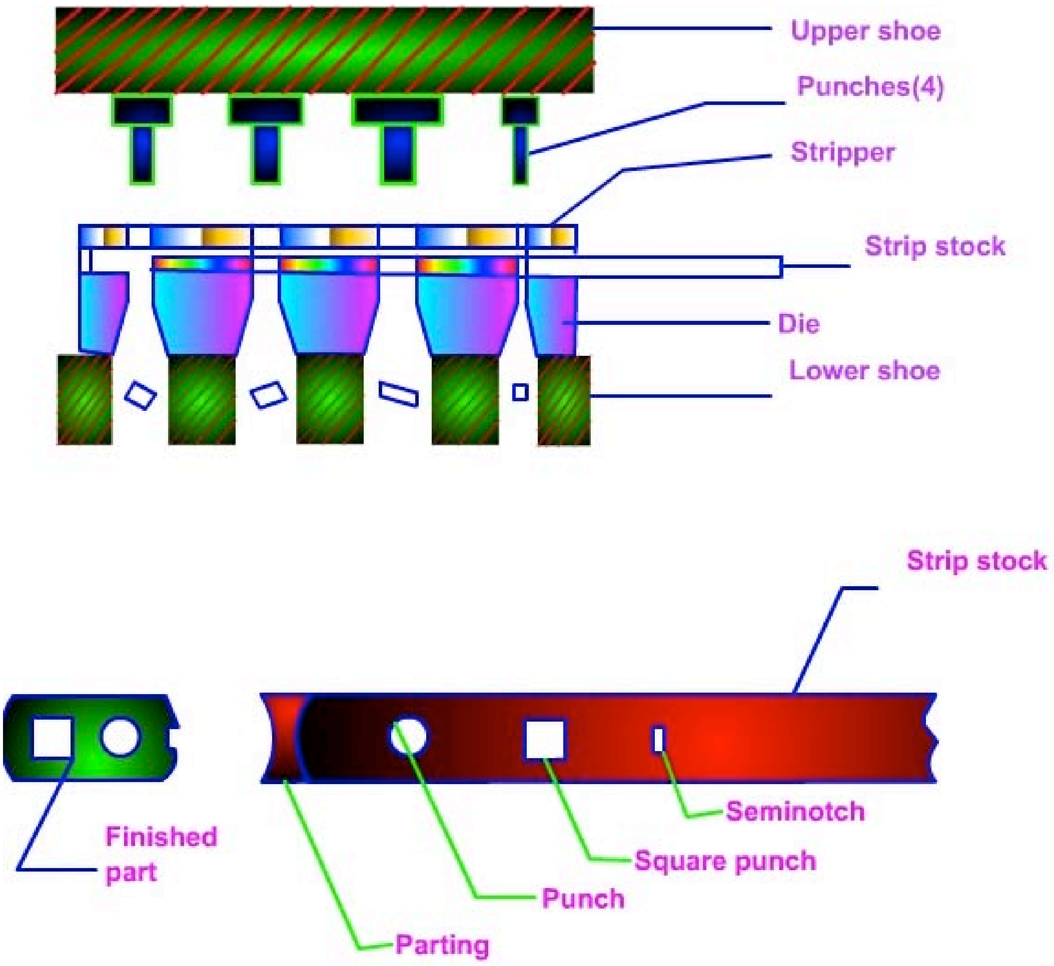


Fig. 1.3.1: Blanking and punching

1.4 Cutting:

Shearing off of the entire sheet for producing a number of pieces of various contours is done by cutting. Perforating, slitting, parting are also cutting operations. Slitting is carried out with a pair of circular blades. The rotary cutters slit the sheet along straight line or along a closed contour. The blades or either rotated by power or kept idling through which the sheet is pulled.
Trimming is a finishing operation in which a previously formed part is finished in its contour by shearing off of the burr and excess material.
Shaving is a finishing operation in which shearing off of burrs from the cut edges is carried out in order to make the edges smooth and also impart dimensional accuracy.
Cut off operation involves removal a blank from a sheet metal by cutting on opposites sides, sequentially. The cut edges need not be straight.
Punching of holes of different contours is called perforating. Slotting is making elongated holes such as rectangular holes in sheet metal.
Cutting off a small part from the edge of a sheet is called notching.

1.4 Fine blanking:

It is a finishing operation in which shearing is done with small clearances – about 1% - and close tolerances in order to achieve dimensional accuracy. It is a single step finishing operation. Square and smooth edges are produced applying clamping force on the blank. This prevents distortion of the sheet during operation. A hold down ring or pressure pad with a v-shaped projection is used for holding the top side of the sheet tight during the application of the shear force. At the bottom of the sheet a pressure pad is also used. A triple action press with individual control of the die, punch and pressure pad is used for the operation. Usual sheet thickness ranges between 0.5 to 12 mm.

Material loss in cutting off operations involving sheet metals may be as high as 30%. Arranging the shapes to be cut on the sheet properly so that waste is reduced is called nesting. CAD is used nowadays for this purpose.

1.5 Shearing and forming tools:

A punch with flat tip is seldom used for shearing because the required load is higher. This is due to the fact that the entire thickness of the sheet is sheared simultaneously. The area over which shearing happens at a given instance can be reduced by making the punch end beveled. For thick sheets, beveled punches are preferred because there is considerable reduction in shear load. Single or double bevels are common in case of circular punches. In such cases, lateral rigidity is to be ensured. Die and punch are made of tool steel or carbide.

Forming using hand operated presses is limited to finishing operations. Mechanically or hydraulically operated presses are used for high volume sheet forming. Mechanical presses are quick-operating whereas hydraulic presses are slow-operating but have long strokes.

Clamping pressure or hold down may be required in some sheet forming operations in order to hold the sheet during forming. This will prevent wrinkling of the sheet. In double acting presses, one stroke may be utilized for hold down.

Compound dies are those which have several dies in a single setup. Such dies can be used for making several operations in a single stroke for improved productivity.

Progressive forming refers to the successive forming of the different stages of forming a part using the same tool set with a number of strokes. Making of washers is an example of progressive forming. First a hole is punched during first stroke. Then the sheet is moved to the next position when the blanking operation is carried out. Simultaneous punching and blanking operations can be made in the same stroke using different punches.

Transfer dies are applicable where different operations are to be carried out on the same sheet successively on a series of stations, along a straight path or a circular path.

Example 1:
The shear strength of a cold rolled steel is 300 MPa. Determine the punch force required for making a blank of 120 mm diameter from a strip of 3 mm thickness ofthe above material. What is the maximum punch force required?

Theoretical punch force requires can be calculated from the shear strength.

F = Shear strength X perimeter of the blank X thickness of blank = $300\pi120X3$ = 339.4 kN

Maximum punch force can be calculated using the equation:

$F_{max} = 0.7\sigma_u tL$

Assuming σ_u = 2 Shear strength = 2X300 = 600 MPa

Fmax = 474.8 kN

Example 2:
A cold rolled steel sheet with a shear strength of 350 MPa and a thickness of 3 mm is to be subjected to blanking operation. The diameter of the blank to be obtained is 130 mm. What is the appropriate die and punch diameter and punch force required for the operation?

The clearance for blanking operation can be taken to be 0.075.

Punch and die diameters for blanking operations are given by:
Dia of punch = Db-2c = 130 – 2X0.075 = 129.85 mm
Dia of die = Blank diameter = Db = 130 mm

Punch force = τLt = 350πDt = 428.61 kN

Sheet metal operations - Bending and related processes

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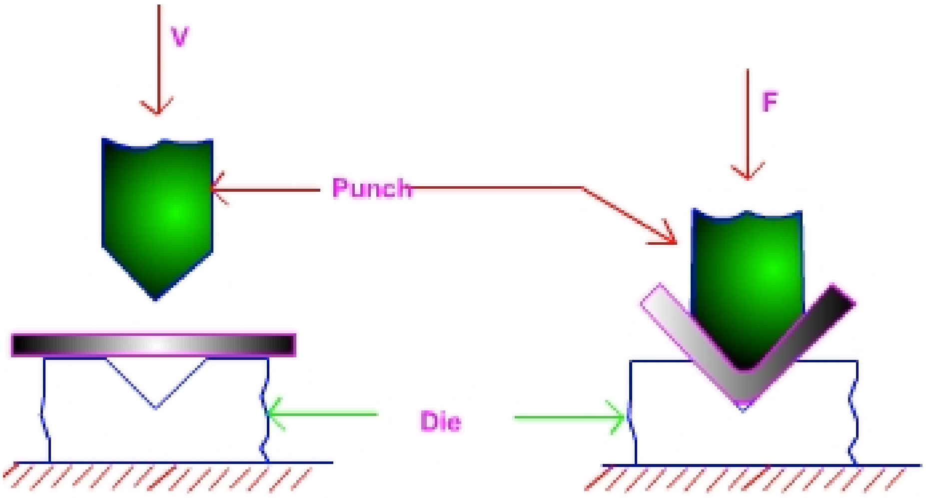
1.Quiz-Key.. Error! Bookmark not defined.

1.Bending and related processes:

1.1 Sheet metal bending

Bending of sheets and plates is widely used in forming parts such as corrugations, flanges, etc. Bending is a forming operation in which a sheet metal is subjected to bending stress thereby a flat straight sheet is made into a curved sheet. The sheet gets plastically deformed without change in thickness. Die and punch are used for bending. If a v shaped die and punch are used, the bending is called v-bending. If the sheet is bent on the edge using a wiping die it is called edge bending. In this process, one end of the sheet is held like a cantilever using a pressure pad and the other end is deformed by a punch which moves vertically down, bending the sheet. Usually, edge bending is done in order to obtain an angle of 90°.

During bending of a strip, the material outward of the neutral axis is subjected to tensile stress. Material inside is subjected to compressive stress. Bend radius R is the radius of curvature of the bent sheet inside the bending. The neutral axis remains at the center of the thickness of the sheet for elastic bending. For plastic bending, however, the neutral axis shifts towards the inside of the bend. The rate of elongation of outer fibers is greater than the rate of contraction of inner fibers. Therefore, there is a thickness reduction at the bend section.



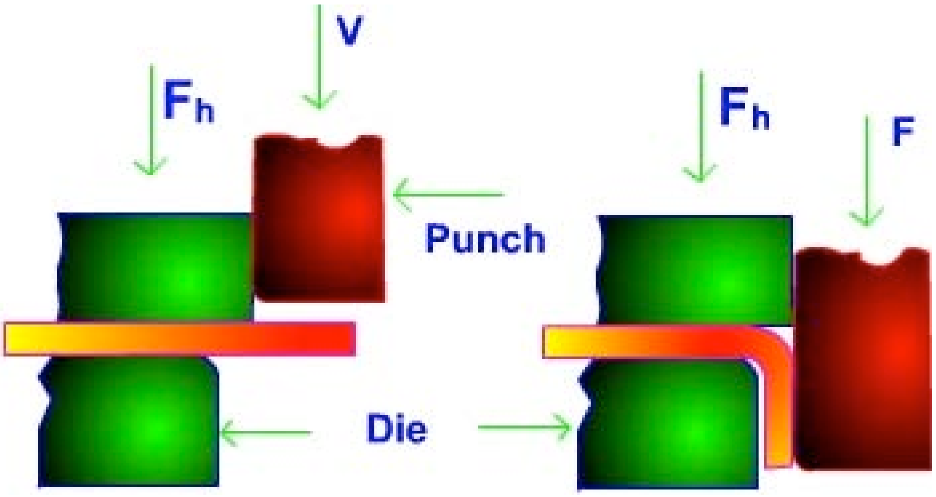


Fig. 2.1.1: V-bending and edge bending operations

U-Bending.swf **V-Bending.swf**

Fig. 1.1.1A: U bending and V bending animations

1.2 Theory of bending:

In plastic bending, we ignore the thickness reduction. Therefore, we assume that the neutral axis remains at the center of the sheet thickness. Consider a sheet of thickness t, subjected to bending so that it is bent to a radius of curvature of R. We can ignore strain along the width direction. Let α be the bend angle.
Bend allowance is the arc length of the neutral axis in the bend area. It is an important design parameter. It is given by:

$L_b = \alpha(R+kt)$, where k is a constant which is equal to 0.5 for ideal bending- neutral axis remains at center. K = 0.33 to 0.5 for R<2t or R>2t. respectively.

We can write the strain on outer fiber or inner fiber as (both are equal):

$$e = \frac{1}{(\frac{2R}{t})+1}$$

In actual bending, the outer fibers stretch more than the inner fibers getting shrunk. This difference in strain between outer and inner fibers increases with decrease in radius of bending or decrease in R/t. Beyond a certain minimum R/t the tensile strain on outer fiber may reach so high a value that the material outside starts cracking. The particular radius at which cracks appear on the outer surface of the bent sheet is called minimum bend radius. It is usually given in terms of the sheet thickness, t.

The following table gives minimum radius for some materials:

Table 1.2.1: Minimum radius for bending

Material	Soft	Hardened
Aluminium alloys	0	6t
Low carbon steel	0.5t	4t
Titanium alloys	2.5t	4t

Note, that a minimum bend radius of zero means that the sheet can be bent on itself.
In order to obtain an expression for minimum bend radius, the true strain of a material during uniaxial tensile test at fracture can be equated to the strain in bending.

$\ln(Ao/Af) = \ln(1+e) = \ln(1+\frac{1}{(\frac{2R}{t})+1})$

From this, we obtain:

R/t minimum = $\frac{1}{2r} - 1$, where r is reduction in area of the sheet during bending.

Or, $R_{min}/t = 50/r - 1$, in which r is expressed as percent area reduction. This expression is applicable for reduction in area less than 0.2.

For 50% area reduction, R=0 which means the material can be folded on itself.

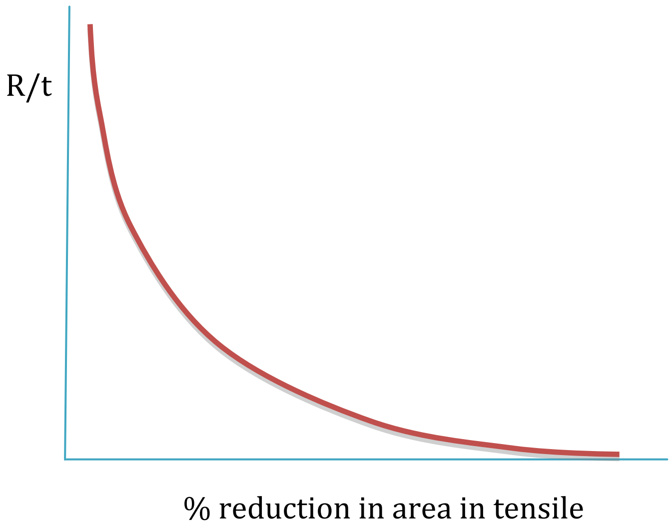


Fig. 1.2.1: Minimum bend radius versus percent area reduction

The above graph shows the variation of minimum bend radius with respect to percent area reduction.

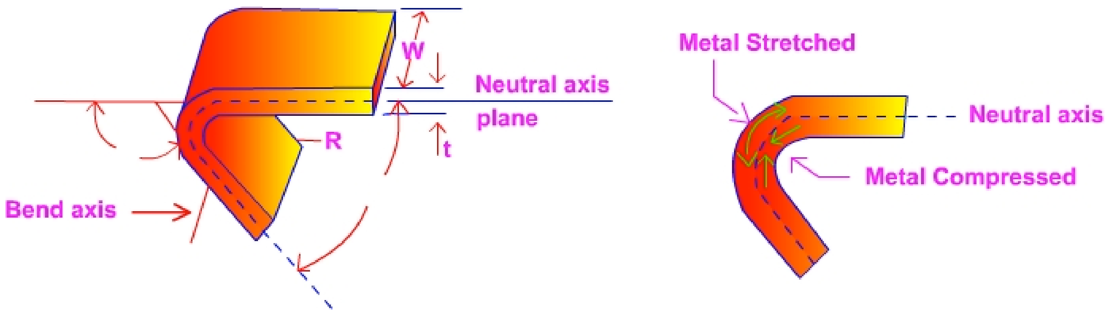


Fig. 1.2.2: Bending – terminology and geometry

In bending the ductility of the sheet metal plays very important role. If the ductility is lower, the minimum bend radius is larger. Similarly, a state of biaxial stress in bend region may also reduce ductility on outer fibers. For larger values of width to thickness ratio (w/t) of the sheet, the state of biaxial stress can be expected. State of biaxiality reaches when w/t reaches a value of 8. Larger w/t ratios reduce the critical strain required for fracture. As a result the bend radius will be higher. Narrow sheets undergo crack at the edge because the state of stress along edge is more biaxial than at center. Wider sheets, when subjected to larger radius of bend, undergo crack at center because the center is subjected to more biaxial state of stress. In order to increase the minimum radius, sheets are polished or ground.

Ability to undergo bending, called bendability can be improved by subjecting the material to hydrostatic stress. This improves the ductility (percent area reduction). Inducing compressive stress on outer fibers may also increase the bendability. Rough edges of the sheet reduces bendability because the rough edges can easily crack during bending. Cold working of the edges can also lead to cracking. Edge cracking may also happen due to inclusions or anisotropy of the material due to operations such as rolling having been cariedout on it.

1.3 Springback:

Elastic recovery of the sheet after the bend load is removed is called springback. Even after plastic deformation, small elastic recovery may happen in ductile materials, after removal of load. In bending springback reduces the bend angle. Similarly, the bend radius after springback is larger. Springback will be larger for materials having lower elastic modulus and higher yield strength. Springback increases for a sheet with higher width to thickness ratio as the stress state is biaxial or plane stress.

After releasing the load during bending, the bend radius changes. However, the bend allowance does not change. Therefore, we have:

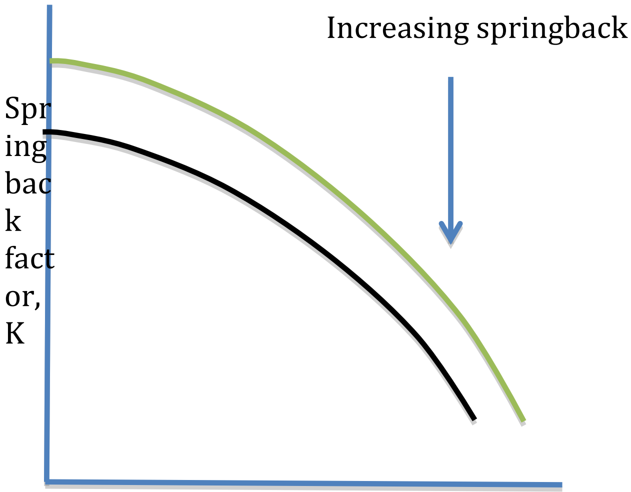
$$L_b = \alpha i(Ri+t/2) = \alpha f(Rf+t/2)$$

Or, $$K = \alpha f / \alpha i = \frac{(\frac{2Ri}{t}+1)}{(\frac{2Rf}{t}+1)}$$

K is springback factor, Ri is initial radius of curvature before releasing the load, Rf is radius of curvature of bend after releasing the load.

K = 1 indicates that there is no springback. K=0 means there is total elastic recovery as in springs.

Springback depends on R/t ratio. As the ratio increases, the spring back also increases, as indicated by decreasing K value from the graph below.



R/t

Fig. 1.3.1: Springback factor versus bend radius

Negative springback is a situation in which the bend angle becomes larger after removal of load. Negative spring back happens in v-bending. The material bends inward after the load removal due to large strains.
Another expression for springback in terms of bend radius is:

$$\frac{R_i}{R_f} = 4\left(\frac{R_iY}{Et}\right)^3 - 3\left(\frac{R_iY}{Et}\right)+1$$

Springback decreases as the yield strength decreases.

Overbending is one way of compensating for springback. Another way is by subjecting the sheet to compressive stress – coining between die and punch before bending. This is called bottoming. High temperature can also reduce springback, as the yield stress is reduced. Stretch bending, in which the sheet is subjected to tensile stress at the time of bending can also reduce springback. This is because excess tensile stress applied during stretching reduces the bending moment for bending.

1.4 Bend force:

The force required for bending a sheet of thickness t, length L, to a radius R is given by:

$$F = \frac{YLt^2}{2\left(R+\frac{t}{2}\right)}\tan(\alpha/2)$$

The maximum bend force is given by:

$F_{max} = kUTSLt^2 / W$

Where UTS is ultimate tensile strength of the material, W is die opening width

k→ takes values between 1.2 to 1.33 for v-die bending and 0.3 to 0.4 for wiping.

1.5 Other bending processes:

Long and narrow sheet metals are usually formed or bent to required shapes, using a hydraulic or mechanical press. Simple long die and tool and cast iron or carbon steel die materials make this press brake forming process a very widely used process.

Air bending is the bending of sheets freely between an upper roll or punch and a lower die freely. In **roll bending**, a pair of rolls support the plate to be bent and the upper roll applies the bend force. In continuous roll bending, called roll forming, a series of rolls are used. The strip or sheet is passed through the rolls, making the bending in stages. Panels, frames, channels etc can be formed by this process. Rolls are made of gray cast iron and chrome plated. Basic force involved in roll forming is bending, not compression as in rolling.

Beading or curling: In this process, the edge of the sheet is bent into a circular or other contour shape of the die itself, or formed into a curl, using one die or a pair of dies. Beading of ends of a sheet improves its stiffness by enhancing its moment of inertia at the edges. Hinges are examples for beading.
Hemming refers to a bending process in which the end of a sheet is bent into itself, to increase stiffness or protect the edge of the sheet, or to avoid sharp edge.

Seaming is assembling of two hemmed sheet ends in order to form a joint of the sheets. Double seams are used for water tight or air tight joints, such as that used in food beverage containers.

U shapes, corrugations, channels, tubes can be formed by bending sheet metals to specific shapes using a pair of shaped dies.

Flanging: Bending the edge of sheets to 90 degrees for improving their stiffness or for assembly is called flanging. If the angle of bend is less than 90 degrees, it is called flaring. Either compressive or tensile hoop stress is involved in flanging process.

Flanges can also be made by combining piercing the sheet with a punch and followed by expansion of the pierced edge using an expander punch. This process is called dimpling. A bullet shaped piercing punch is also sometimes used.

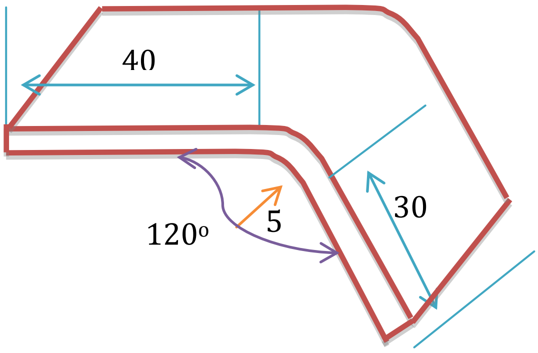
1.6 Tube bending:

Bending of tubes is more difficult than sheets because tubes tend to undergo folding or they may collapse if subjected to bending stress. When a tube is subjected to bending, the tube wall on the outer side of the bend is subjected to tensile stress, while that inside the bend is subjected to compression. As a result the tube wall thins out on the outer and thickens on inside of bend. Excessive compressive stress inside the bend results in wrinkles or folds. Usually, tubes are bent after filling the inside with sand. Sand fill prevents the tube from buckling during bending. Internal flexible mandrels or plugs are usually used during tube bending. Thick tubes may not require internal fills or plugs. Various methods of tube bending such as draw bending, stretch bending and compression bending are shown in figure below:

The minimum radius of bending is generally 1.5 times the tube diameter for thin walled tubes with internal mandrels used. Minimum bend radius in the case of bending of thick walled tubes without mandrels is 3 times the tube diameter.

Example:

A certain sheet metal(tensile strength = 500 MPa, E = 200 GPa), having a thickness of 3 mm and width 40 mm is subjected to bending in a v-die with opening of 22 mm. The other dimensions are as shown in figure. What are the blank size and bending force required? Ignore springback.



From the figure we see the bend angle = 60°

The length of the blank can be determined as:

L = 40+30+Bend allowance

Bend allowance is given by:

$L_b = \alpha i(Ri+t/2) = \alpha f(Rf+t/2) = 6.8$ mm

L = 76.8 mm

Now, the bend force can be determined from the expression:

$F_{max} = kUTSLt^2 / W$
k = 1.33

F = 1.33X300X76.8X9 / 22 = 12535.85 N

Sheet metal operations - Other sheet metal forming processes

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1.Other sheet metal forming processes:

In this lecture we primarily focus on sheet metal operations that may not require forming press. Stretch forming, hydro forming, spinning are some of such processes.

1.1 Stretch forming:

Stretching of a sheet metal, by holding its ends or edges and bending it over a form block, simultaneously is called stretch forming. It is a process involving tensile force. Rigid die is used in the process. Materials with good ductility alone can be stretch formed. Further, in this process there is very little springback because of absence of nonuniform deformation or due to constant stress gradient across the thickness. This is due to high tensile stress applied. Aircraft wing panels, automobile door panels, window frames are some of the parts produced by this process. Tensile forces as high as 9 MN are used in forming aluminium skins for aircrafts. A single form block or punch is used alongwith gripping jaws. The forming is performed using hydraulically operated ram. First the sheet is bent around the form block. Then it is gripped and stretched applying large tensile force until it plastically deforms. The force required for the operation can be roughly calculated from the expression:

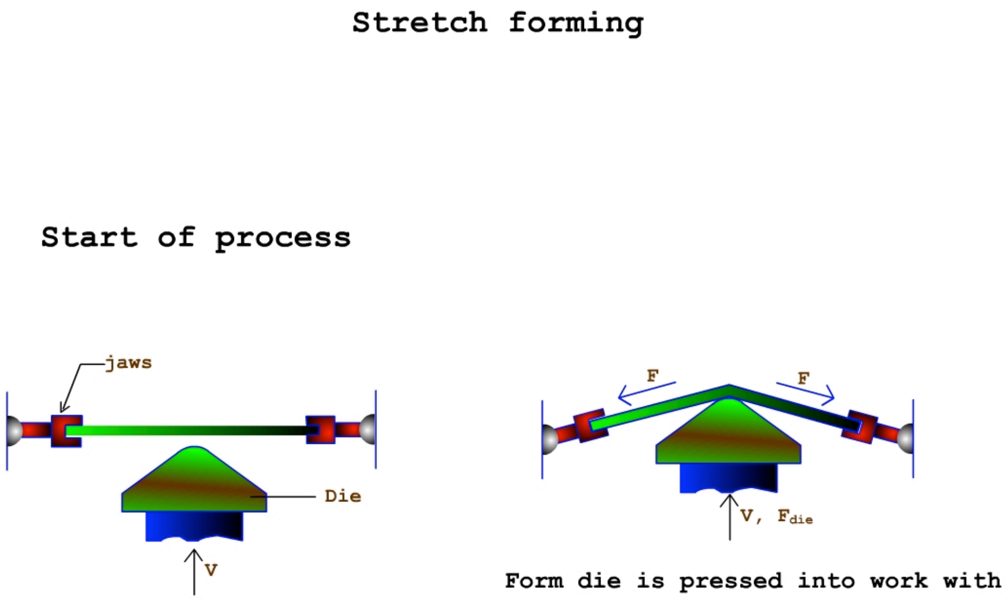
$F = Y_f L t$

Where L is length of the sheet perpendicular to direction of stretching and t is thickness of sheet.

It can be shown that the strain gradient during stretch forming is:

$$\frac{d\varepsilon}{dr} = -\frac{\frac{\varepsilon}{r}}{n}$$

From this expression we understand that the regions where strain is higher get more wok hardened. This renders the less strain hardened neighborhood to undergo larger strain thereby reducing the strain gradient and keeping constant strain gradient. This enables processing of highly strain-hardenable materials with ease.



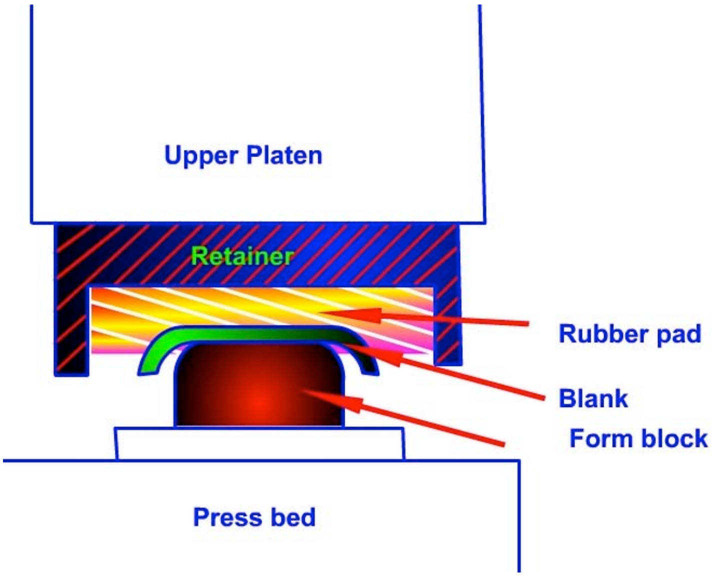
Form die is pressed into work with force F_{die}, causing it to be stretched bent over to form;
F= Stretching force;

Fig. 3.1.1: Stretch forming

1.2 Rubber forming and hydroforming:

In rubber forming, a polyurethane or rubber pad is used as the die material instead of a rigid material. Such materials have resistance to abrasion, good fatigue life. Pressures of the order of 10 MPa are typical in rubber forming. It is also known as Guerin process. A form block made of rigid material is used. The blank is placed over the form block. The rubber pad, which is attached to the ram, is then forced down on the sheet metal. Scratches on the sheet metal are avoided because the sheet is not in direct contact with the tool.

In hydroforming, fluid pressure acting over a flexible membrane is utilized for controlling the metal flow. Fluid pressure upto 100 MPa is applied. The fluid pressure on the membrane forces the sheet metal against the punch more effectively. Complex shapes can be formed by this process. In tube hydroforming, tubes are bent and pressurized by high pressure fluid. Rubber forming is used in aircraft industry.



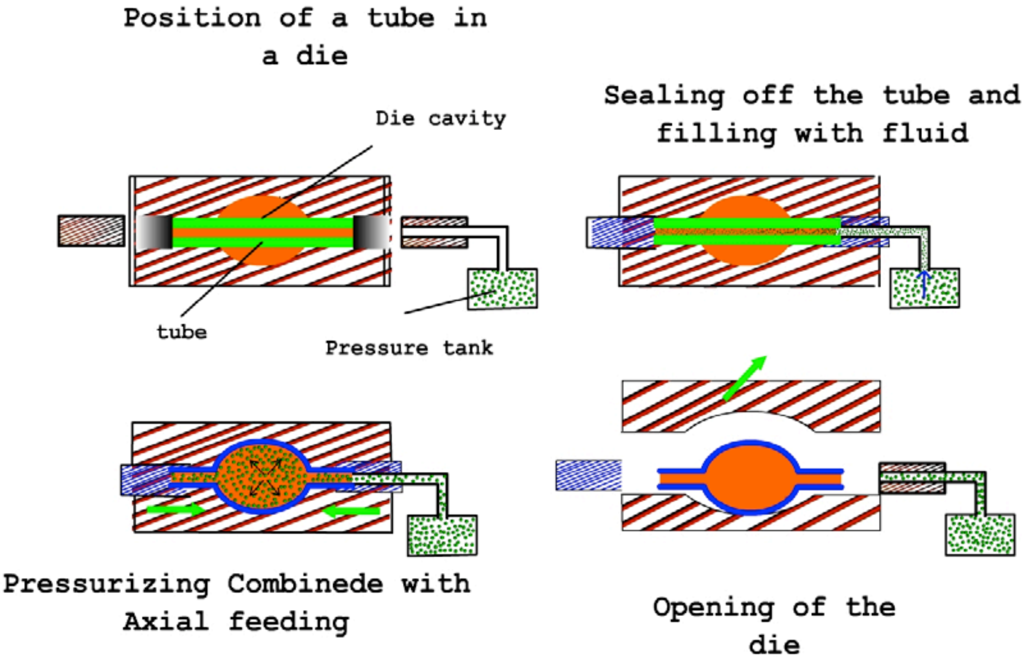
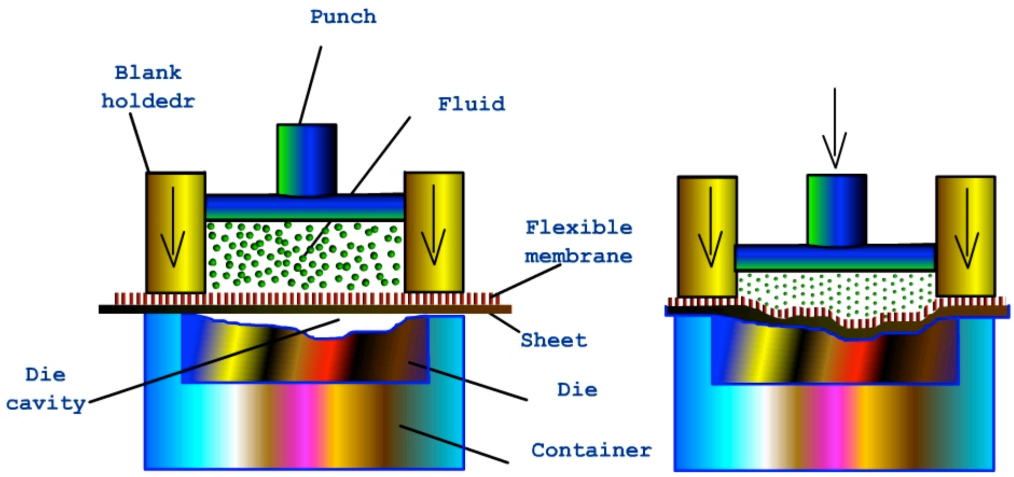


Fig. 3.2.1: Tube hydro forming

Schematic Illustration of Sheet Hydroforming



Sheet hydroforming, for the production of hollow parts

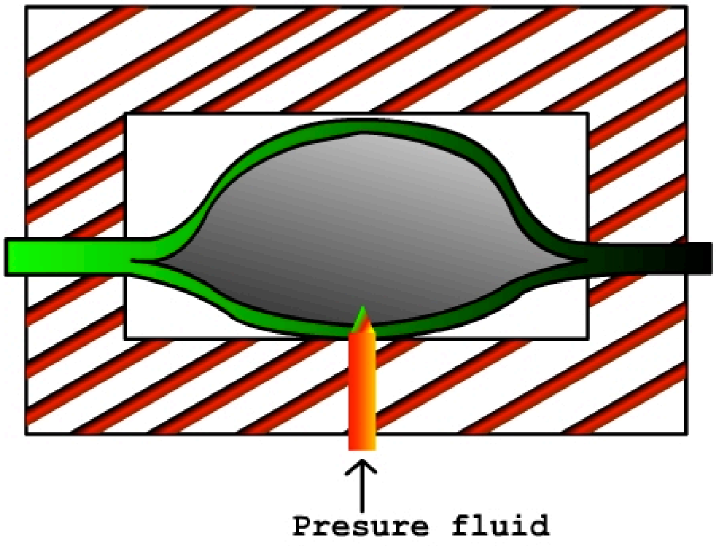


Fig. 3.2.2: Sheet hydro forming

1.3 Spinning:

Forming deeper axi-symmetric parts from a blank against a rotating mandrel is known as spinning. Rigid rollers are used as the spinning tool. The shaping of the circular blank over a rotating mandrel is done using rigid roller tool. In conventional spinning, the blank is bent around the rotating mandrel using a roller. Spun parts may have diameter as large as 6 m. Utensils are made by conventional spinning, as this process is cheaper. Blank diameter is larger than the diameter of finished part in conventional spinning.

Shear spinning: Otherwise known as flow turning or hydrospinning, shear spinning involves reduction of thickness and the finished part has same diameter as the blank. Blanks upto 3m diameter can be shear spun. Large plastic deformation of the blank is involved in this process. The process involves thinning of the blank. The maximum spinning reduction r is given by:

$r = (t_o - t_f)/t_o$

where t_f is the final thickness after spinning. It is obtained from the expression:

$t_f = t_o \sin\alpha$, where α is semi-cone angle of the mandrel.

The tangential force during spinning is given by:

$Ft = u t_o \sin\alpha \; f$, where f is the feed.

The maximum reduction in thickness to which a blank can be subjected to by spinning without any crack is defined as spinnability. It is determined by spinning a circular blank over an ellipsoid mandrel. The maximum spinnability corresponds to a maximum reduction in area of 50%.

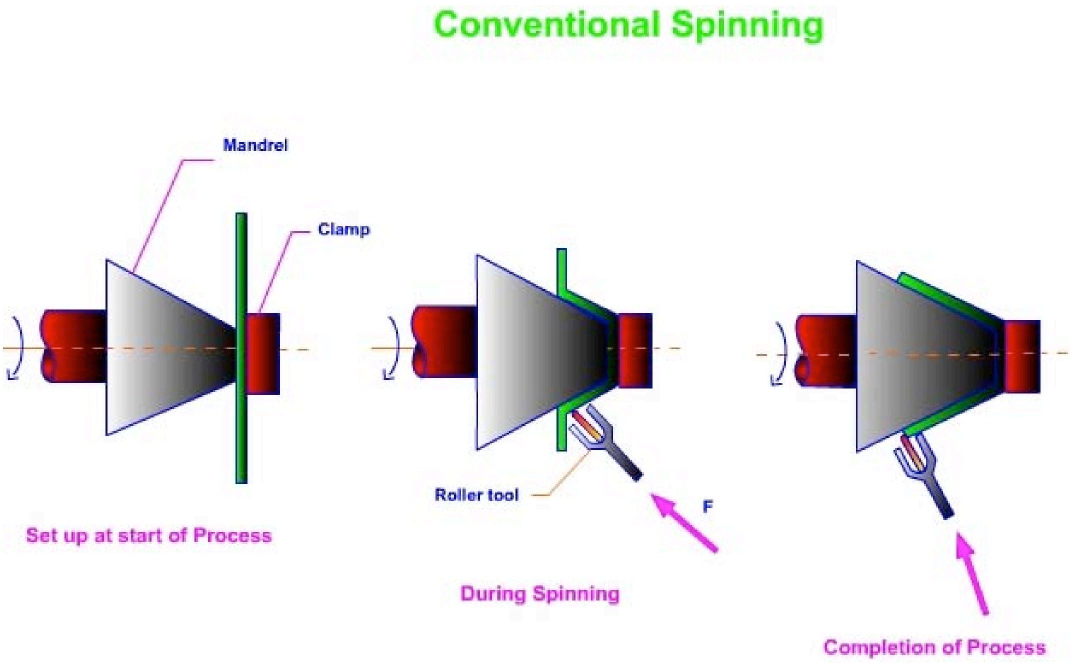


Fig.1.3.1: Sheet spinning

1.4 Tube spinning:

In this process, reduction in wall thickness and increase in length of tubes is achieved with the help of a rotating mandrel and roller. Both internal and external spinning can be carried out. Roller can be moved forward or backward. Different profiles of the tube can be made in this process. The tangential force required is written as:

$F_t = Y_f(t_o - t)f$, f being the feed and Y_f being flow stress of the material.

Tube spinning is used in forming of rocket parts, automotive components etc.

1.5 Unconventional forming of sheet metal:

High energy rate forming processes such as explosive forming, electrohydraulic forming etc are discussed in this section.

1.5.1 Explosive forming:

In this process the high energy released due to explosion of an explosive is utilized for forming of sheets. No punch is required. A hollow die is used. The sheet metal is clamped on the top of the die and the cavity beneath the sheet is evacuated. The assembly is placed inside a tank filled with water. An explosive material fixed at a distance from the die is then ignited. The explosion causes shock waves to be generated. The peak pressure developed in the shock wave is given by:

$$p = k\left(\sqrt[3]{w}/R\right)^a$$

k is a constant, a is also a constant. R is the stand-off distance. Compressibility of the medium and its impedance play an important role on peak pressure. If the compressibility of the medium used is lower, then the peak pressure is higher. If the density of the medium is higher, the peak pressure of the shock wave is higher. Detonation speeds as high as 6500 m/s are common. The metal flow is also happening at higherspeed, namely, at 200 m/s. Strain rates are very high. Materials which do not loose ductility at higher strain rates can be explosively formed. The stand off distance also determines the peak pressure during explosive forming. Steel plates upto 25 mm thickness are explosive formed. Tubes can be bulged using explosive forming.

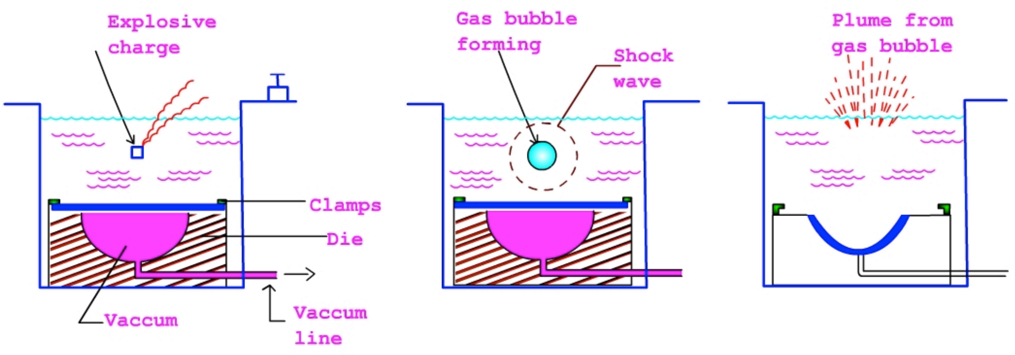


Fig. 3.5.1.1: Explosive Forming

3.5.2 Magnetic pulse forming:

This process is also known as electromagnetic forming. In this sheet metal high velocity forming, the electrical energy stored in a series of capacitors is discharged through a magnetic coil. Mechanical force is induced due to the induced magnetic field on the work by the eddy current of the coil, opposing the original magnetic field. The forces repel each other. The work material is thus forced against the die cavity. Tube swaging, flaring, bulging etc can be made by this process.

3.5.3 Electrohydraulic forming:

A pair of electrodes immersed in water get connected by a thin wire. The high current discharged through the wire from a series of capacitors outside, creates spark. This in turn produces shock waves. The shock waves propagate through the water medium and help in forming the part. It is suitable for small parts as the energy generated in this process is lower than that in electromagnetic forming.

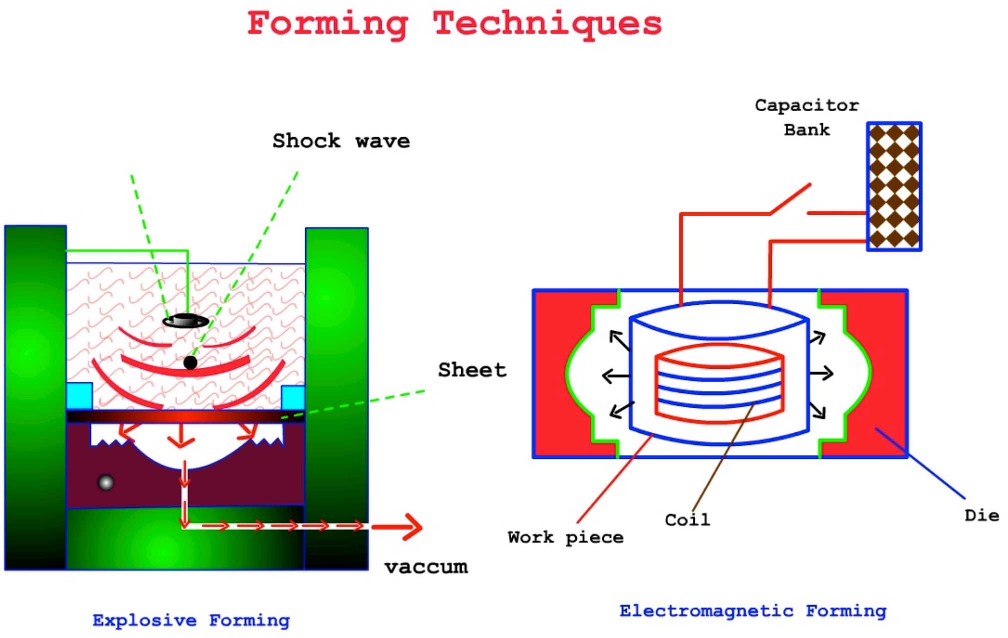


Fig. 5.3.3.1: Explosive forming and electromagnetic forming

3.5.4 Superplastic forming:

Some metals and alloys are capable of undergoing large uniform elongations – upto 2000% - without localized deformation, under certain conditions. Very fine grain structure is required – grain size of 10-15 microns. Superplastic forming is carried out at elevated temperature of 0.4 Tm. Materials with fine grains as well as resistance to grain growth at elevated temperatures can be superplastically formed. Materials with high strain rate sensitivity (m>0.3) resist necking even at large stresses. Aluminium, zinc alloys, nickel alloys are formed into complex shapes using superplastic forming. It is carriedout at slow strain rates-less than 0.01 s^{-1}. Flow stress required during superplastic forming is very low – less than 30 MPa. The alloys, which undergo superplastic forming, have low strength and high ductility. Difficult to form alloys can be formed under superplastic conditions. Moreover, tools required need not have high strength. No residual stresses are induced in formed products. This process alongwith diffusion bonding is used for fabricating intricate parts. First the sheets are diffusion bonded. Then the unbounded regions are expanded inside a mold using air pressure. Such processes are used in aerospace industries for making stiff structural components. Alloys of titanium and aluminium are superplastically formed for making parts of aircrafts such as fuselage, ducts etc.
Superplastic forming does not leave any residual stress on the formed part due to low stresses involved.

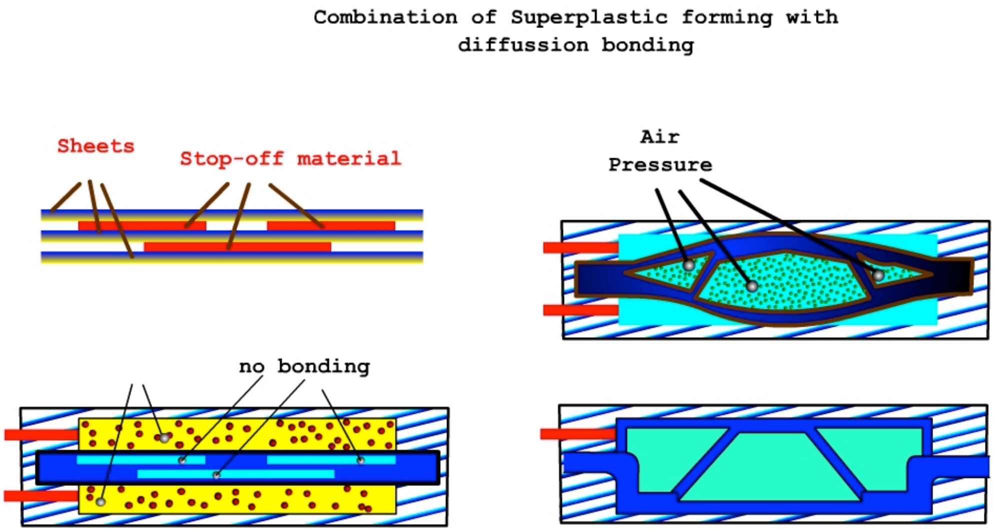


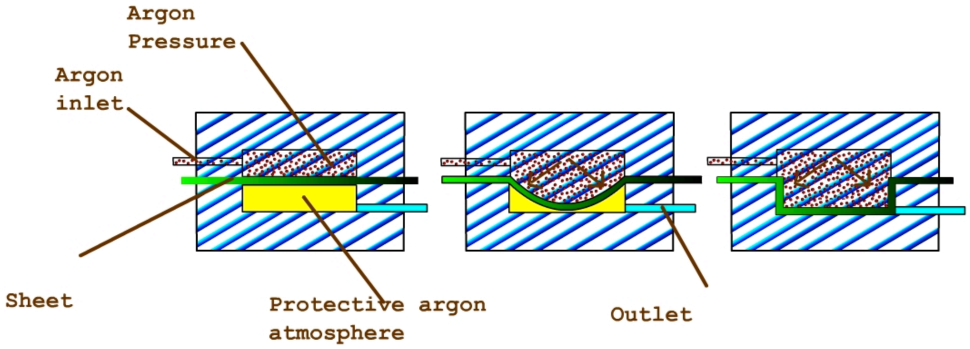
Fig. 3.5.4.1: Superplastic forming with diffusion bonding

The technology of superplastic forming involves combination of blow forming or thermoforming and diffusion bonding.

3.5.5 Blow forming / vacuum forming:

In blow forming, a pressure difference, created on both sides of the sheet metal causes the sheet metal to get stretched and formed to the shape of the die. Argon gas is used for pressurizing the sheet metal on one side, whereas on the other side, a low pressure of argon gas is maintained. Such back-pressure avoids cavitation of the sheet metal. Cavitation is the formation of inter-granular voids. Sometimes, vacuum is maintained on the other side of the sheet. This process is called vacuum forming.

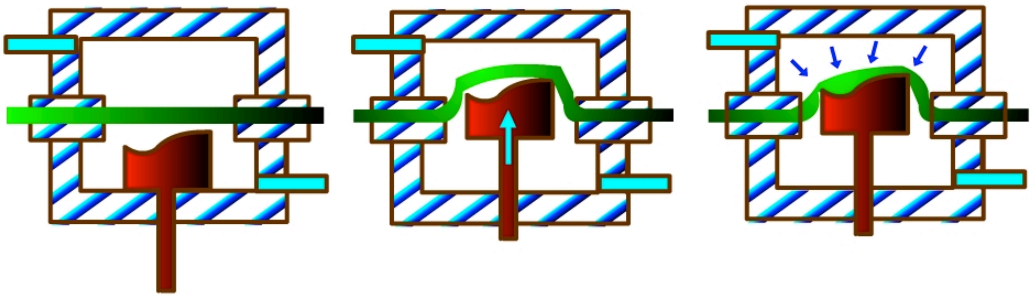
Illustration of the blow-forming tchnique for super plastic forming



3.5.6 Thermo forming:

This process is often used for forming plastics. Firstly, a male die stretches the sheet superplastically. Then gas pressure is used to force the sheet which has been stretched against the die.

Illustration of a possible set-up for the
thermo-forming technique



3.5.7 Laser/Plasma forming:

If thermal stresses are induced locally in materials, localized deformations can occur. Such deformations can be utilized for forming of sheet metals. Laser or plasma can be used as heat source for causing localized heating. There may not be external stress required for the forming process. However, laser-assisted forming may require small external forces for forming operations such as bending, tube forming, embossing etc.

Cup drawing or deep drawing

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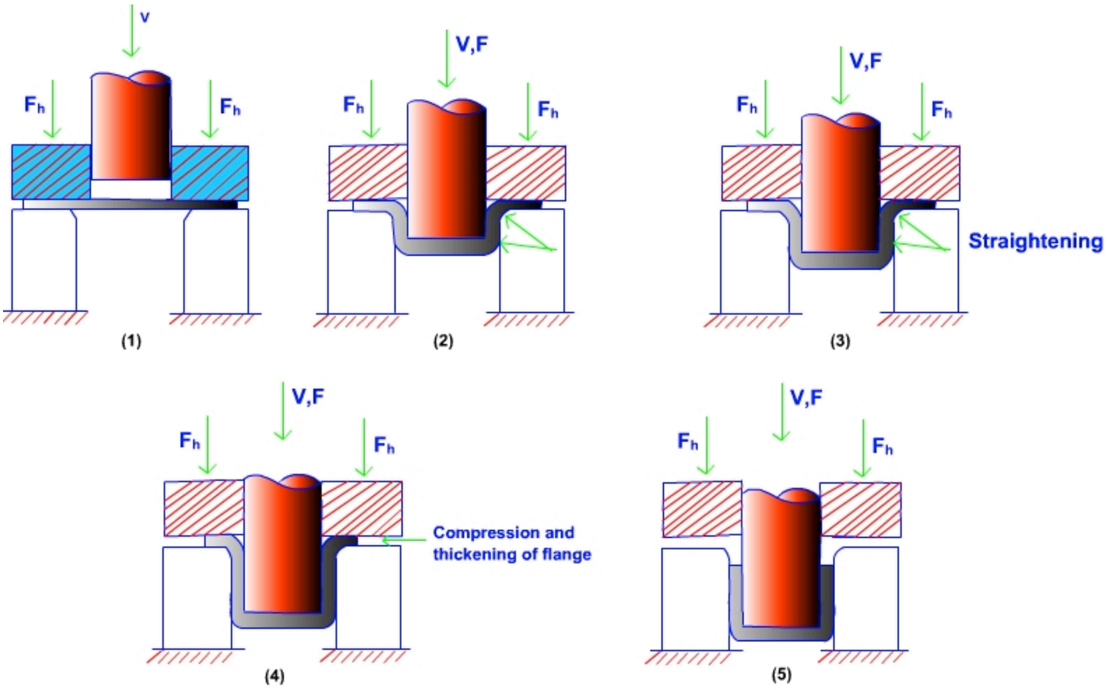
1.Cup drawing or deep drawing

1.1 Deep drawing process

Cup drawing or deep drawing is one of the widely used sheet metal forming operations. Cup shaped objects, utensils, pressure vessels, gas cylinders, cans, shells, kitchen sinksetc are some of the products of deep drawing. In this process, a sheet metal called blank is placed on a die cavity, held in position using a holding plate or holding ring and pressed against the die cavity using a solid punch. The sheet metal attains the shape of the die cavity with flat bottom. Both die and punch should be provided with corner radius in order to avoid shearing of the sheet.



Stages in deformation of the work in deep drawing:
1) Punch makes initial contact with work
2) Bending
3)Starightening
4)Friction and Compression
5) Final cup shape showing effects of thining in the cup walls.
V =Motion of punch
F =punch force
F_h=blankholder force

Fig. 1.1.1:Cup drawing process – sequence of operation

During drawing of sheet into the die, there is thickening of the sheet upto 12%. Therefore, clearance is provided between the punch and die. The radial clearance therefore is equal to the sheet thickness plus the thickening of sheet. Punch pushes the bottom of the sheet into the die cavity. The flat portion of the sheet under the holding plate moves towards the die axis, then bends over the die profile. After bending over the die profile the sheet unbends to flow downward along the side wall. The vertical portion of the sheet then slips past the die surface. More metal is drawn towards the center of the die in order to replace the metal that has already flown into the die wall. Friction between holding plate and blank and that between die and blank has to be overcome by the blank during its horizontal flow.

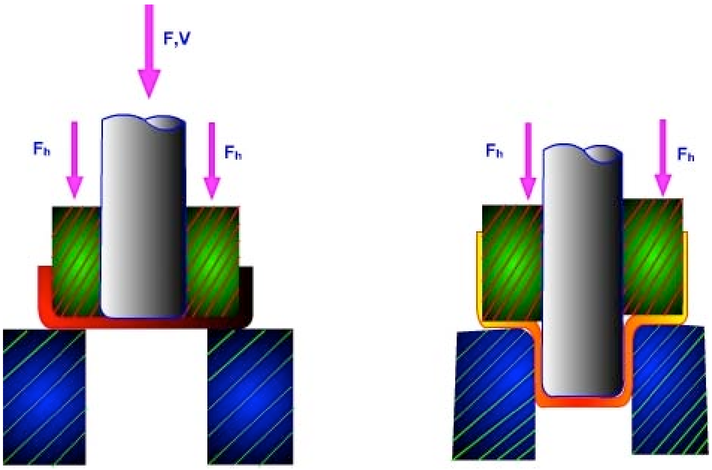


Fig. 1.1.2: Redrawing of cup

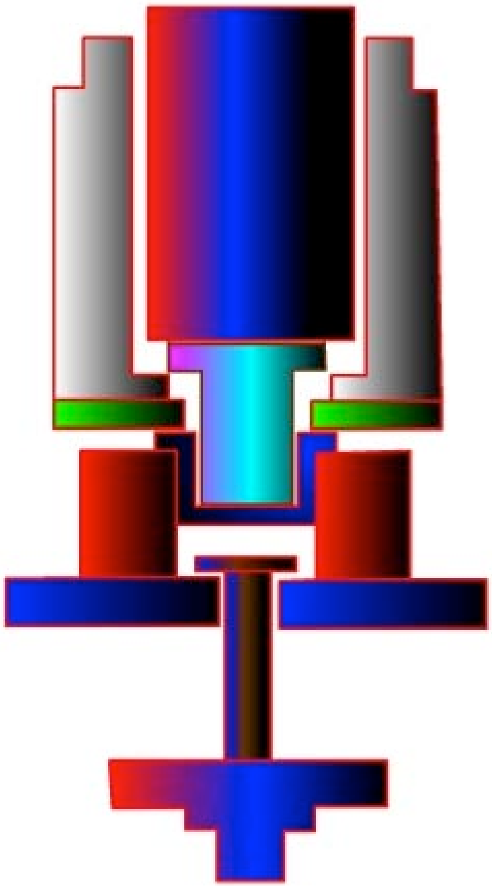


Fig. 1.1.3: Deep drawing with double action press

1.2 Analysis of Cup Drawing:

Tensile stress is induced on the sheet at various locations within the die cavity. Maximum tensile stress is caused near the end of punch, at the profile of punch, because the sheet bends over the edge of the punch due to tensile stress. The sheet unbends along the cup wall. Necking of the sheet takes place near the punch profile due to excess tensile stress, resulting in fracture. The sheet under the holding plate, namely, the flange undergoes compressive hoop stress, radial tensile stress and compressive stress due to blank holding plate. Thickness of the cup wall increases from bottom to top. The die-punch clearance, usually, taken as 1.1t, where t is thickness of the sheet.

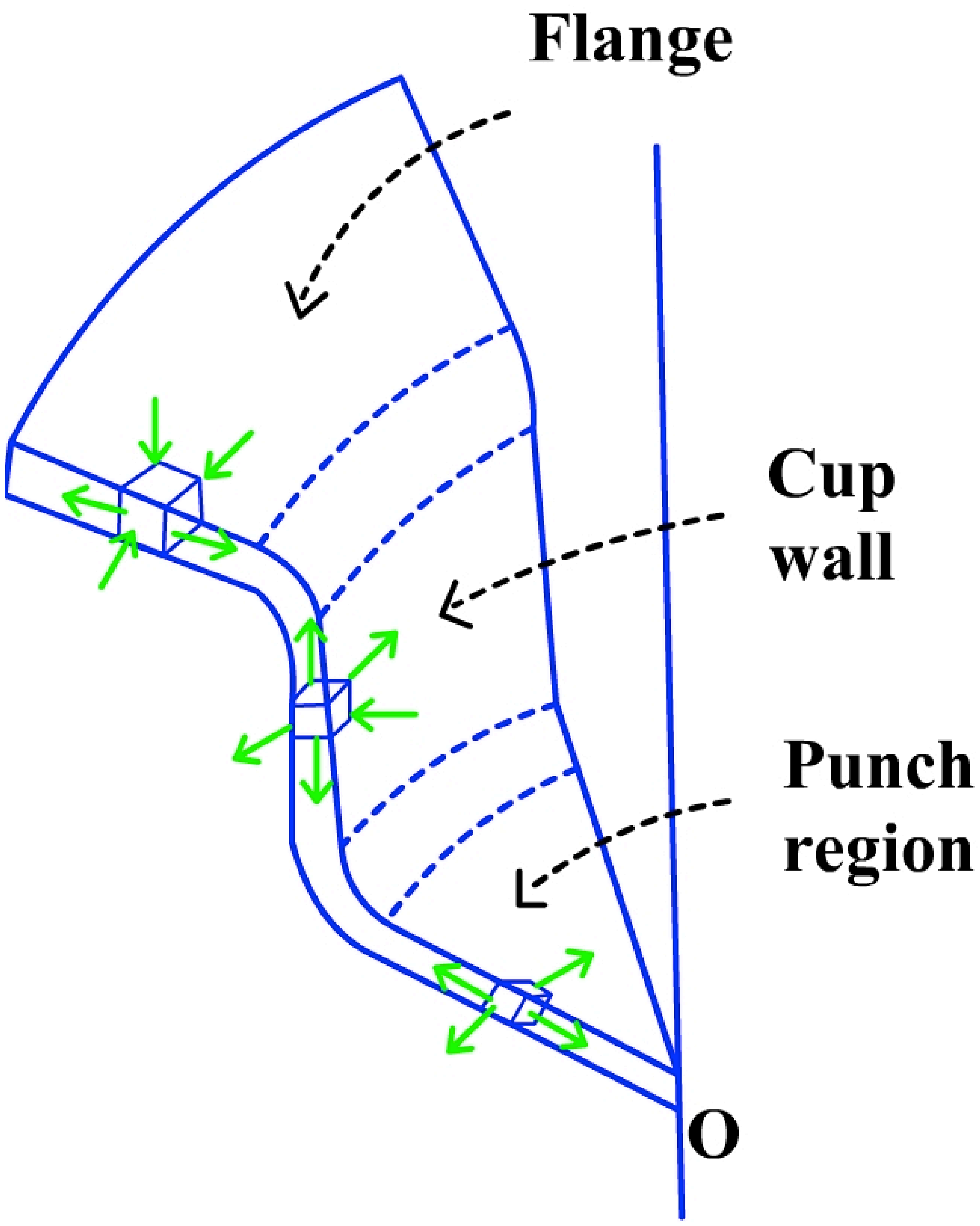


Fig. 1.2.1: Stresses in deep drawing process

Stresses acting on the sheet at various locations are shown in figure. The flange portion of the blank is subjected to a compressive hoop stress due to it being drawn towards the center. It is also subjected to radial tensile stress. The compressive stress of the hold down plate will be acting in the axial direction. If the hoop compressive stress is high or if the metal in the flange is not restrained wrinkling of the metal in the flange happens. To prevent wrinkling, the hold down plate is used. The material of the flange undergoes compressive hoop strain and a radial tensile strain. The result is the metal in the flange, as it flows towards the center, tends to thicken – due to circumferential shrinking. However, due to bending under the punch and die profile, the metal undergoes thinning. The metal at the center of the blank, which is getting pressed by the punch bottom, is subjected to biaxial tensile stress due to the punch. The metal in the gap between die wall and punch is now subjected to longitudinal and hoop tensile stresses. If the clearance is less than the metal thickening on the flange side, the metal in the cup wall is squeezed. This process of thinning of the cup wall is called ironing. In order to reduce thickness and to cause uniform thickness on the cup, ironing is used in some drawing process, employing smaller clearances between die and punch.

The drawing force required under ideal frictionless flow conditions will increase linearly with punch stroke – due to increase in strain on the metal and also because the material gets strain hardened. Friction due to hold down pressure as well as sliding tends to increase reach a peak value and decreases early during the drawing. This is due to the fact that after certain amount of drawing the amount of material under the hold down plate reduces. Ironing force operates during the later part of the process, as sufficient thickening has to occur. About 15% of the total force is spent on bending and unbending of the blank on the die and punch profile. 70% of the total force is required for radial drawing of the material. 10% of the energy goes for overcoming friction.

If the blank hold down force is too high or if draw beads are used under the hold down ring, the material around the punch will begin to stretch instead of being drawn. This may lead to localized necking or diffuse necking depending on strain rate sensitivity, lubrication, punch geometry. On the other hand, a lower hold down pressure makes the metal flow freely into the die cavity.

The material which occupies the length represented by the difference between the die and punch radii is likely to undergo wrinkling – folding due to hoop compressive stress. This is due to the fact that the diameter of the blank has become sufficiently smaller. Therefore, the smaller material is unable to support the hoop stress and hence wrinkles. This happens especially when the hold down pressure is insufficient and the thickness of sheet is too small and the material flow is pure drawing mode.

Sachs has given an approximate expression for total drawing force, which is given below:

$$F= [\pi D_p t 1.1 Y ln\left(\frac{D_o}{D_p}\right)+ \mu(2H\frac{D_p}{D_o})]e^{\frac{\pi\mu}{2}}+B \qquad 1.1$$

D_p is punch diameter
D_o is blank diameter
H is hold down force
B is force for bending and unbending
T is blank thickness
Y is yield strength of the material

In deep drawing material just above the bottom of the punch is subjected to circumferential tensile stress and longitudinal tensile stress. Punch force acting on the bottom of the cup is transferred to the side of the cup. The narrow ring of metal just above the bottom of the cup is subjected to plane strain condition. As a result, failure of the cup easily happens in this zone due to necking induced by the tensile stress, leading to tearing. Punch force is shown to vary with the stroke of the punch. It is difficult to predict the punch force in deep drawing. However, an expression for maximum punch force is given by:

$$F_{max}= \pi D_p t_o UTS(\frac{D_o}{D_p}-0.7) \qquad 1.2$$

UTS is ultimate tensile strength of the material, t_o is initial thickness of blank

The maximum tensile force on the cup which causes tearing can be estimated form the plane strain condition as:

$F_{max} = 2/\sqrt{3}\,\mathrm{UTS}\pi D_p t$ 1.3

In wire drawing the strain hardening exponent n has significant influence on deformation and draw force. Whereas in deep drawing strain hardening does not affect significantly both draw stress and deformation.

Clearance between die and punch is a critical factor in deep drawing. Normally, radial clearances of 7 to 14% of the sheet thickness is common. Too small a clearance may cause shear on the blank. Sharp corner on the punch could cause fracture of the cup along the corner. Too large a radius on the corner of punch may cause wrinkles on the flange. Similarly die corner radius, if small, can cause fracture on the flange. Corner radius is normally 5 to 10 times the sheet thickness.

Blank holder pressure is another important factor. 0.5 to 1% of the ultimate strength of the sheet material is normally taken to be the hold pressure. Too large a hold pressure results in tearing along cup wall. Too low a value leads to wrinkling in flange. An approximate expression for holding force is given based on the initial area of the blank and assuming that the holding pressure is 0.015 times yield strength.

Hold force = $0.015\pi(D_o^2 - (D_p + 2.2t + 2R_d)^2)$ 1.4

Rd is die corner radius.

Thick sheets could be drawn without blank holder. In such case, the limit on the diameter of sheet is governed by: $D_o - D_p < 5t_o$

Drawability and formability of sheet metals

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1.Drawability and formability of sheet metals

1.1 Limiting draw ratio:

In deep drawing, the longitudinal tensile stress on the cup leads to thinning and tearing. There is a maximum size of the blank which can be drawn out without tearing. The limiting draw ratio (LDR) is defined as the highest value of the ratio of the blank diameter to punch diameter which can be drawn out without failure.

LDR = $(D_o/D_p)_{max} = e^{\eta}$ 1.1

Where $\eta$is the efficiency of drawing.

The maximum LDR for efficiency =100% is equal to 2.7.

The above can be proved as followed:

Consider the deep drawing of a cup. The maximum true strain of the blank during deep drawing is:

$$\varepsilon_{max} = \ln\left(\frac{D_0}{D_p}\right) \qquad 1.2$$

For ideal drawing we can write the draw stress = Yε

For maximum or limiting draw, we can equate the draw stress to yield strength of the material.

Y = draw stress = Yε_{max}

From which we get:

$$\varepsilon_{max} = \ln\left(\frac{D_0}{D_p}\right) = 1 \qquad 1.3$$

From the above we get $\frac{D_0}{D_p}$ = e = 2.7 1.4

If we assume an efficiency of 70% the maximum LDR is about 2. That means the maximum reduction possible in single deep drawing step is 50%.

LDR is affected by the punch dia, lubrication, the hold down pressure, and clearance.

LDR is also affected anisotropy of the material of the blank. One way of increasing the drawability of sheets is to impart anisotropy through grain texturing. Anisotropic behavior refers to direction dependency of mechanical properties. Normal anisotropy or plastic anisotropy of a sheet metal is given by the ratio of the width strain to thickness strain.

$$R = \frac{ln\frac{w_o}{w_f}}{ln\frac{t_o}{t_f}} \qquad 1.5$$

Subscript f denotes final dimension.

If the true strain along width is equal to that along thickness direction R =1. That is the case of isotropic material.
On the other hand, if R is very less or higher than unity it indicates considerable anisotropy.

The thickness strains are very difficult to measure. Therefore we may write R using length, applying volume constancy as:

$$R = \frac{ln\frac{w_o}{w_f}}{ln\frac{w_f t_f}{w_o t_o}} \qquad 1.6$$

For rolled sheets, we can consider planar anisotropy, which means the orientation of the test specimen with respect to rolling direction will decide the properties.

Planar anisotropy taken at different angles with respect to rolling direction, averaged out is defined as:

$$\bar{R} = \frac{R_0+2R_{45}+R_{90}}{4} \tag{1.7}$$

The average normal anisotropy value depends on the material structure, grain size, etc.

Typically, for HCP materials $\bar{R}$ values are high. Similarly, finer the grains lower is the value of average anisotropy.

Material	$\bar{R}$
Hot rolled steel	0.8 to 1
Stainless steels	0.9 to 1.2
Aluminium alloys	0.6 to 0.8
Copper	0.6 to 0.9

It has been demonstrated experimentally that as the average normal anisotropy increases, the LDR also increases, almost linearly. It is shown in figure below:

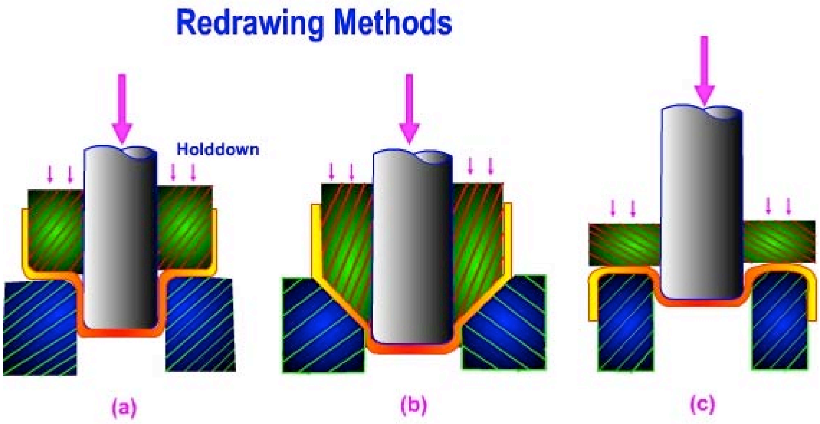
Planar anisotropy of a sheet metal can be given by:

$$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{4} \qquad 1.8$$

A low value of planar anisotropy enhances the LDR.
LDR in crystalline materials can be controlled through anisotropy. Anisotropy can be controlled through grain texture. Texture can be imparted through rolling or other thermomechanical processing. In plane strain stressing of the cup wall, if textured structure can improve the normal anisotropy, LDR will have increased – meaning that drawability has been enhanced. Planar anisotropy sometimes causes a type of defect in drawn cups called earing. Ears are fold like structures that form along the cup length.

1.2 Redrawing:

Redrawing is reduction in diameter and increase in length of a cup which has been drawn to a certain draw ratio. In case of materials which are difficult to draw in one step, redrawing is performed. Generally, during the first stage upto 40% reduction is achieved. In the first redrawing after drawing, maximum of 30% reduction can be set. In the second redrawing stage, 16% reduction is set. In direct redrawing process, the angle of bending undergone by the cup is less than 90^o, thereby reducing the draw force. In reverse redrawing, the outside surface of the drawn cup becomes the inner surface during redrawing. Wrinkling is controlled to a good extent in this process. Friction is higher in redrawing. Therefore larger reductions can not be affected in redrawing.



a) Direct redrawing
b) Direct redrawing with tapered die
c) Reverse redrawing

Fig. 1.2.1: Redrawing

1.3 Formability of sheet metals:

Formability of sheet metal is the ability of the sheet metal to undergo forming to the desired shape and dimensions, without failure. Sheet metal operations are very complex. Therefore, simple tensile or compressive tests may not be sufficient to evaluate the formability. We can determine the ductility, anisotropy and other parameters from the uniaxial tensile test. A number of other tests have been devised to determine formability of sheet metals.

Cupping tests: In order to reflect the biaxial state of stress involved in drawing, a few tests have been devised to obtain the drawability.

In Erichsen test a sheet metal is placed on the die cavity and clamped with 1000 kg load. A spherical ball of 20 mm diameter is pressed into the sheet using hydraulic force. The test is terminated at the point of maximum load or until a crack forms on the sheet. Erichsen number is the distance through which the sheet has stretched.

Bulge test: A sheet metal clamped around its periphery, is bulged by hydraulic pressure. The depth of penetration before failure is taken to be a measure of formability. This test is also done to study effective stress-effective strain curve for biaxial stress.

Swift test involves pure drawing, while Fukui test combines drawing and stretching, by using a hemispherical punch which produces a conical cup.

1.4 Forming limit diagram (FLD):

Prediction of failure during drawing is possible by construction forming limit diagrams. Circles of a specific pattern are etched on the surface of the sheet metal, by chemical etching or photoprinting. The circles may be 2.5 to 5 mm in diameter. Then the blank is subjected to stretching using suitable punch and draw bead. The deformations of the circles in regions where necking has happened are measured. Lubrication may be used if needed. Major and minor strains on the circles are found from the deformed circle. Circles get deformed into ellipse. If we take a wide rubber plate, draw a circle at the center and stretch the rubber along longitudinal direction. We can see that the circle now gets stretched to an ellipse. On the other hand, if a circle is drawn on the surface of a spherical balloon and the balloon expanded, the circle becomes a larger circle. This means that both minor and major axes have undergone equal strain.

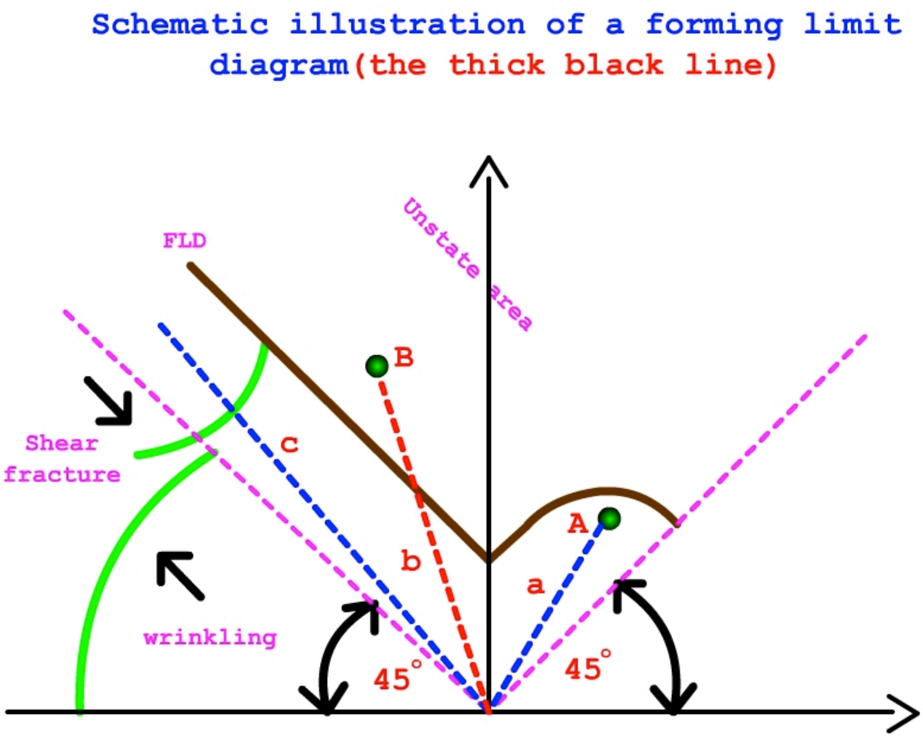


Fig. 1.4.1: A typical forming limit diagram

Length of major axis of the stretched circle minus dia of original circle divided by original dia of circle gives the major strain (engineering strain). Similarly engineering minor strain can be found out. If the minor axis stretches out it represents positive strain. If it shrinks, it is negative strain. By comparing the deformed circles, with original circled we can also predict if the sheet has undergone thinning or not. A larger ellipse is an indication of thinning. After a number of such tests, the forming limit diagram is drawn, between major strain and minor strain. The boundary between safe and failed regions are represented in the forming limit diagram. Any strain represented on the diagram by a point lying above the curve indicates failure. The strain path can be varied by varying the width of the sheet. Different materials have different forming limit diagrams. The higher the position of the curve greater is the formability.

A typical formability limit diagram is known as Keeler-Goodwin diagram. The curves shift upward if the sheet thickness is increased – indicating increase in forming limit. In this diagram, a few straight lines indicating the strain paths are also shown. The vertical line at the center (zero minor strain) represents plane strain. In biaxial strain, both strains are equal. This is represented by the inclined line on right side of the diagram. Simple uniaxial tension is represented on the left side by a line with slope 2:1. This is due to the fact that Poisson's ratio for plastic deformation is ½.

Negative minor strain means there is shrinkage. It is better to have negative minor strain because, the major strain for failure will be higher with negative minor strain.

Some of the factors which affect the forming limit of a material are: strain rate sensitivity, anisotropy, thickness of the sheet, strain hardening etc. The forming limit curve will be shifted upwards for a thicker sheet.

1.5 Hydroforming of sheet metals:

Forming of sheet metals using hydrostatic pressure of a fluid has immense potential for automotive and aerospace applications. Sheet metal products meant for these applications can be formed using hydroforming. Hydrostatic pressure enhances the ductility. Further, it also enhances the LDR. There are two methods of hydrostatic forming of sheet metals, namely hydro-mechanical forming and hydroforming.

1.5.1Hydro-mechanical forming:

In this method of cup drawing, an oil or water chamber underneath the cup contains high pressure fluid. The fluid pressure exerted on the bottom side of the cup ensures that the blank is pressed against the punch, thereby reducing neck formation. The hydraulic pressure also enhances the lubrication between die and blank. This better lubrication improves LDR. If pressurized fluid is supplied onto the edges of the blank, the drawability is further enhanced through reduced friction. Reverse redrawing or redrawing can also be carried out by this process.

1.5.2Hydro-forming:

In hydroforming the fluid pressure is directly utilized for deforming the material. Bulging of tubes is one example for hydroforming. In this process, the high pressure fluid held inside the tube expands the tube at the section where there is no restraint.

1.6Defects in sheet metal formed products:

One of the major defects in drawing of sheet metals is thinning or localized necking, which leads to crack formation or tearing. During cup drawing, material near the punch radius is subjected to maximum thinning and therefore, the bottom of the cup gets separated. Providing large radius on the punch or reducing the punch load may eliminate this defect.

Radial cracks in the flange of the cup is an indication of poor ductility of the material.

Buckling of the flange material due to high compressive stress leads to wrinkling. The critical circumferential compressive load is lower for thin sheets. We may imagine that each circumferential element of the metal acts like a column subjected to buckling. Increasing the hold down pressure will eliminate wrinkling.

Large grain size of sheet metals results in poor surface finish and the surface develops orange peel effect, which is surface roughness. This defect can be prevented using fine grained material for drawing.

Surface defects called stretcher strains occur on low carbon steel sheets due to yielding. Depressions form on the surface oriented along directions of maximum shear, namely, 45 degrees. They merge and form rough surface. The entire surface is covered by stretcher strains. Temper rolling or skin rolling treatment given at room temperature will eliminate stretcher strains. In temper rolling, a small cold reduction of 1 to 2% is given to the sheet.

Formation of wavy edge on top of the cup, called earing, happens due to anisotropy of the material, especially planar anisotropy. Primarily, preferred orientation of grains is responsible for this defect.

Example 1:

A sheet is subjected to tensile stretching during which it undergoes a stretching of 25% and also undergoes decrease in thickness of 12%. What is its limiting draw ratio?

Solution:

The limiting draw ratio can be found from the relation between R and LDR.

R = width strain/thickness strain = $\dfrac{ln\frac{w_o}{w_f}}{ln\frac{t_o}{t_f}}$

We are given $L_f/L_o - 1 = 0.25$ or $L_f/L_o = 1.25$

Also, $1 - t_f/t_o = 0.12$, Or$t_f/t_o = 0.88$

From volume constancy, $L_o t_o w_o = L_f t_f w_f$

$w_o/w_f = L_f t_f/L_o t_o = 1.25X0.88 = 1.1$

Therefore, R = 0.746

From the graph between R and LDR, we get the LDR for R=0.746, assuming planar anisotropy.

LDR = 2.25

Example 2:A certain sheet metal has a normal anisotropy of R = 2.25. Assuming no change in thickness during the process, determine the maximum cup height to diameter ratio.

Solution:

From graph, we have LDR = D_o/D_p = 2.75 for R=2.25.

Applying constancy of volume before and after drawing of cup,

We can solve for $h/D_p = 1.64$.

Example 3:

A blank of diameter 200 mm and thickness of 3 mm is drawn into a cup using a punch of diameter 12 mm. What is the maximum force required for the deep drawing process if the tensile strength of the material is 800 MPa?

Solution:

We can estimate the punch force from the expression:

$$F_{max} = \pi D_p t_o UTS\left(\frac{D_o}{D_p} - 0.7\right) = 22/7 \text{ X } 12 \text{ X } 3 \text{ X } 800 \ (200/12 - 0.7)$$

Punch force = 1.44 MN.

Powder forming

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1. Powder forming:

1.1 Introduction

In conventional manufacturing processes such as forming, casting, machining etc, the raw materials used are often in the form of solid materials or solids melted to liquid state. A new class of manufacturing process, called powder metal forming has emerged in recent times. Powder forming utilizes metal or alloy powders as raw materials in order to obtain finished parts of high precision and accuracy, at competitive costs. Considerable saving in raw material could be achieved in powder forming, as very little after-machining is required for the formed powder metal components. Powder forming is a net-shape forming operation which is capable of producing complex shapes with wide range of properties, in high volumes. Flexibility of material composition, coupled with tailor-made properties imparted to the powder metal components due to wide range of microstructures are added advantages of the process. Materials, such as ceramics, which are difficult to process through casting because of their high melting point temperatures, could be processed through the powder metallurgy (P/M) route without difficulty. One of the inherent disadvantages of powder forming is porosity in the finished part, which significantly reduces the mechanical strength, hardness, wear resistance and fatigue strength of the formed parts. Large size components are difficult to produce through powder metal processing. However, P/M processing is competing with casting, forging, machining and extrusion of conventional wrought materials, due to the enhanced formability of powder metal preforms. Examples of parts made by P/M process include gears, connecting rods, pistons, hydraulic valves, valves, etc. Nearly 65% of the components used in modern automobile are manufactured through P/M. Aerospace and defence sectors are increasingly utilizing P/M parts for high precision applications.

1.2 Powder metal processing:

Powders are very small size particles having diameters from 0.1 to 200 micrometers. Powders of nano size (less than 200 nano meters) are possible. Human hair typically has a diameter of 100 micrometers. (1 micrometer = 10^{-6} m). Powder metallurgy involves production of metal or alloy powders and compacting them to required shape in green condition, followed by sintering at high temperature to achieve the required strength. The general steps involved in powder metallurgy processing are: a. Production of metal powders, b. Powder mixing or blending, c. Powder compaction, d. Sintering and e. Post-sintering operations. The following section briefly discusses the above-mentioned steps.

1.2.1 Production of metal powders:

The raw material for the production of metal powders may be the bulk metal, compounds of the metal, salts and oxides of the metal. The nature of the powder produced and its characteristics such as particle shape, size, composition etc depend on the method of production of the powders. The commonly employed methods of producing metal powders are: atomization, reduction, mechanical alloying, electrolytic deposition etc.

Atomisation: In this process, the molten metal or alloy is injected through a small orifice and the emerging liquid stream is broken into fine droplets by a jet of air, steam or inert gas. The fine droplets, when cooled form fine particles of varied shapes. The particle size formed depends on the size of the orifice, temperature of the metal, pressure or velocity of the atomizing gas stream etc. Atomisation produces finer powders with spherical shape and smooth surface. In rotating electrode method of atomization process, the molten metal from the tundish is made to fall on a rotating disk, which breaks the molten liquid into small droplets. Centrifugal atomization involves a spinning disk with a consumable electrode inside a helium filled chamber. Centrifugal force breaks up the molten electrode into small droplets, which cool down to fine particles.

---→figure of atomisation

Electrolytic deposition: Metal powders of high purity and finer size could be produced by this process. In this process, metal powders are produced by electrochemical reaction involving aqueous solution or fused salt.

Reduction of oxides: Metal oxides of fine size are reduced with reducing gases such as carbon monoxide, hydrogen to pure metal. Spherical, porous powders of uniform size could be produced by this process.

Ball milling: Two or more metal powders are ball-milled in a high speed chamber using tungsten or carbide balls. This process results in production of mechanically alloyed intermetallics. Powder particles of nano size could be produced by ball-milling process. Ball milling is also used for producing fine particles from brittle metals.

Elementary metal powders or alloy powders with various alloying elements can be produced by the above processes. Alloy powders ensure physical and structural homogeneity of the finished part, but requires higher compaction pressures to achieve a given density.

1.2.2 Powder metal particle characteristics:

Particle characteristics such as shape, size and size distribution are important for processing metal powders successfully into finished parts.
Particle shape is expressed by shape factor. Shape factor is ratio of surface area to volume of particles multiplied by equivalent diameter of a sphere of same volume. Higher shape factor indicates long, flaky particles.

Surface area of particles is measured by BET method. The adsorption of some species in solution as a monolayer on the powder surface and subsequent calculation of area of a single molecule gives the estimation of surface area.
Particle size is measured by sieve analysis. In this process, a known mass of the metal powder is passed through a series of sieves of different mesh size. A mesh

size of 100 has openings with diameter of 150 microns. Higher mesh size indicates smaller particle size. Particle size can also be studied using optical or electron microscopes. Particle size distribution is important from the point of powder processing such as compaction. Size distribution is usually expressed as percentage mass of the powders which pass through a sieve of particular size.

Compressibility of powders gives an indication of the extent to which the metal powder can be compacted and densified by the application of a certain force. It is expressed by a curve between density of compact and applied stress. Larger compressibility means larger forces are required for compacting a given powder.

1.2.3 Powder mixing and compaction:

Blending refers to mixing of same kind of metal powders whereas, mixing refers to the uniform mixing of powders of different kind. Mixing or blending of elementary powders is carried out in mixers or ball mills or attritor mills under inert or controlled atmospheres. Oxidation and explosion of powders should be prevented during mixing by ensuring inert atmosphere in the mixer. Powder size could be controlled using high speed ball milling of the powders.

Compaction of metal powders is the process of pressing green powders inside closed die-punch assembly. Powders are compacted by applying suitable pressure through punches. Lubrication is necessary to reduce inter-particle friction and particle-die wall friction. Lubricants such as graphite powder, zinc stearate powders are usually blended with metal powders before compaction. Density of compacts is important from the point of view of handling the green compacts. In compaction the particles come closer and establish contact. A heterogeneous mix of particle shape and size will promote uniform density of compacts. Softer powders promote higher green density. Similarly, higher compaction pressure leads to higher density of the compact. Admixed lubricant also promotes higher green density. The density of the compact is not uniform along the compact height due to non-uniform transfer of compact pressure from the punch to the compact. The distribution of compaction pressure along the height of a powder compact is given by the exponential expression:

$p_x = p_o \exp -\frac{4\mu k x}{D}$, where po is pressure on the contact surface between punch and powder compact. k accounts for inter particle friction, μ is friction coefficient along die wall.

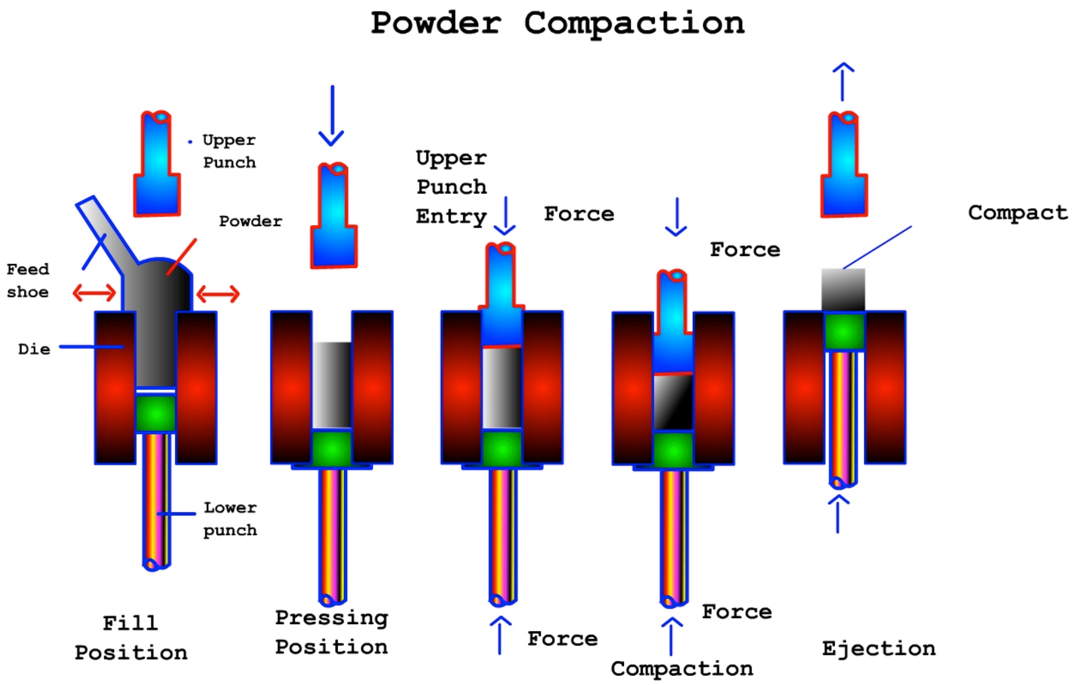

Fig. 1.2.3.1: Powder compaction process sequence

Compaction die and punch are often manufactured from die steel, though Compacting pressure varies for different metal powders. Alloy powders require higher compaction pressures. Normally the pressure varies from 300 to 800 MPa for iron and from 50 to 300 MPa for aluminium powders. Hydraulic presses of capacity upto 300 tons is commonly used for compaction. Usually the maximum density achieved in uniaxial compaction is limited to 95%. In order to achieve near full density in compaction cold or hot isostatic pressing could be employed. Cold isostatic pressing involves the application of hydrostatic pressure using a hydraulic medium on the powder contained inside a flexible container such as rubber or leather bag. Pressures upto 1000 MPA are applied. Hot isostatic pressing is carriedout in a container made of sheet. The metallic container with the powder is heated to high temperature – upto 1300 K, uniform pressure of

100-200 MPa is applied, in order to obtain 100% density. Uniform densification is achieved in isostatic pressing.

Powder rolling in another compaction process, in which the powder is fed into the roll gap of a pair of rolls. The compacted strips are passed onto a sintering furnace. Thin sheets long and continuous can be produced by powder rolling.

Powder extrusion – both hot and cold extrusion can be done at room temperature or at elevated temperature. Higher extrusion pressures are normally required for powder extrusion.

In powder injection molding, the metal powder is mixed with 30 – 40% polymer binder, squeezed inside a molding die, at 400 to 500 K, similar to plastic injection molding, debinding is done at 400 K and sintered. PIM process is commonly used for making intricate parts out of metals such as steels, titanium, copper, tool steel etc. It has high productivity, suitable for mass production and is a competitive process as against forging or casting.

Warm compaction is carried out at slightly higher temperatures but below temperatures on-half the melting temperatures. Warm compaction is often used for hard, abrasive powders, as the higher temperature of compaction softens the powders.

----→ Powder rolling diagram

1.3 Sintering:

Green compacts do not have sufficient strength and they may collapse even under small loads, because the particles are loosely bonded with each other. They also contain porosity between the particles. In order to eliminate porosity and to establish metallurgical bond between powder particles, sintering is carried out after compaction. Sintering is the process in which the compact is heated to a temperature below melting point in order to achieve chemical bonding of particles by the process of interparticle diffusion, plastic deformation, grain formation and grain growth. If the sintering temperature is higher than the melting temperature of one of the metallic components of the compact, then liquid phase sintering occurs. Liquid phase sintering enhances the density of the compact.

Sintering is to be performed in controlled atmosphere in order to prevent oxidation of the surface of the compacts. For ferrous materials, nitrogen-hydrogen gas mixture is used as sintering atmosphere. Cracked ammonia is often used as source of nitrogen and hydrogen. Other gases such as argon, helium, nitrogen are also used as sintering atmosphere.

During sintering, the following stages are known to occur:

Particle bonding by necking

Neck growth

Pore channel closure

Pore shrinkage

Various factors influence the sintering process. Some of the factors are: sintering temperature, sintering time, sintering atmosphere.

Sintering temperature is often within 90% of the melting temperature of the metal. Higher sintering temperatures promote higher densification.

Larger sintering time often leads to higher sintered density. Similarly, higher initial compact density results in higher sintered density. Vacuum sintering of stainless steels leads to better densification.

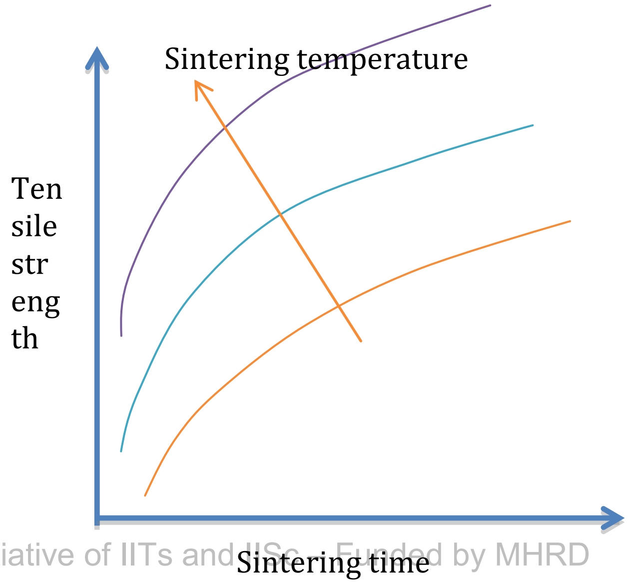

Fig. 1.3.1: Effect of sintering temperature and time on tensile strength

Hard metal powders or ceramic powders are often sintered by a process known as spark plasma sintering. In this process, the metal powders, contained in a graphite mold are subjected to high current discharge while getting compacted. This ensures near-full densification.

During sintering, the compact undergoes shrinkage upto 5%. Volumetric shrinkage during sintering can be estimated using the expression:

$$V_{sinter} = V_{green}\left(1-\frac{\Delta L}{L_o}\right)^3$$

Where L_o is initial length.

Typical sintering temperature and time for some of the common metals are given below:

Material	Sintering temperature, K	Time, minutes
Iron	1275 – 1425	10 – 45
Copper, brass	1035 – 1175	10 – 45
Stainless steel	1375 – 1575	30 - 60
Tungsten	2626	480
Aluminium	873	20

Sintered density greatly influences the mechanical properties of the components. Higher density enhances the tensile and fatigue strengths. Ductility is also improved by reduction in porosity.

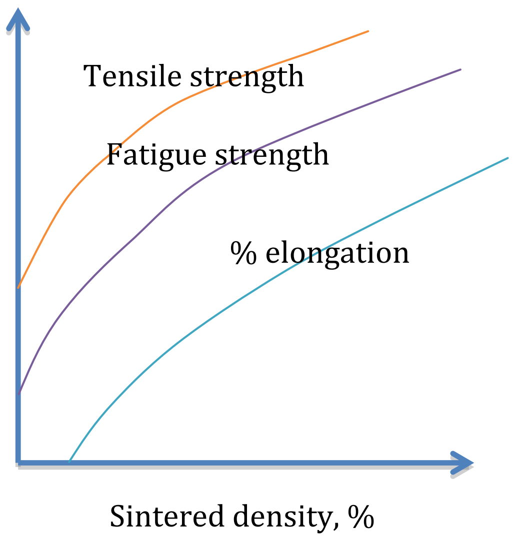

Fig. 1.3.2: Effect of sintered density on mechanical properties

1.4 Post sintering processing:

Tensile strength, ductility and fatigue strength of powder metal parts are considerably degraded by the presence of porosity in sintered material. Porosity may be present in the form of interconnected pores or individual voids. Porosity is helpful for some applications such as bearings and filters. Pores retain the lubricating oil in sintered bearings. High strength applications require pore-free p/m parts. Additional operations may be necessary after sintering in order to eliminate porosity in sintered parts.

Some of the important post-sintering operations which help improve the density of the sintered material are: Forging, extrusion, repressing, infiltration. We discuss these operations in the following section:

1.5 Powder forging:

The sintered metal/alloy preform is subjected to upsetting , repressing or forging inside closed dies, so that the desired final shape of the part is achieved in a single step. Forging can be done at room temperature or at elevated temperature – commonly at 0.5 to 0.7 times the melting temperature of the alloy. Cold forging is common for non-ferrous alloys such as alloys of aluminium.

Ferrous alloys demand forging at high temperature due to their reduced formability and high melting temperatures. Forging often results in density upto 99% or 99.5% of theoretical density of the alloy.

Often it is economical to combine sintering and hot forging in a single step. First the green compact is heated in a furnace up to sintering temperature for the required duration. It is immediately followed by hot forging of the sintered preform by transferring it from the furnace to the forging die. This way considerable saving in energy could be achieved. Cold forged parts have good surface finish and dimensional tolerances. However, hot forging requires lower loads and easy flow of material occurs. In upset forging, there is always the chance of occurrence of surface cracks due to excess tensile stress. In closed die forging such surface cracks generally avoided. Further, closed die forging of sintered material does not require flash.

----------→ Diagram of forging

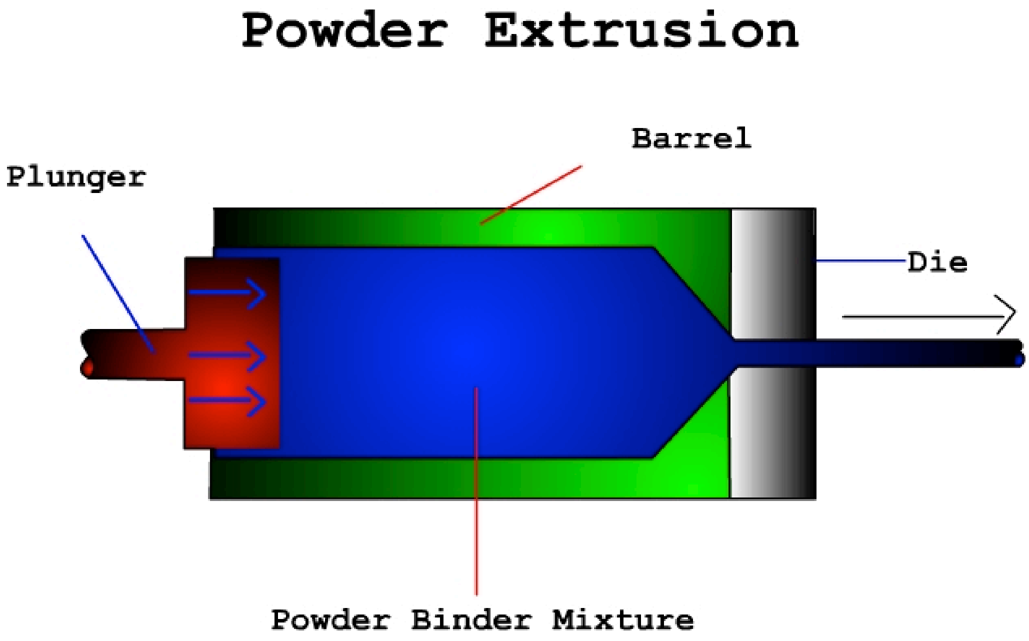

Fig. 1.5.1: Powder extrusion process

Repressing: The sintered preform is subjected to flow constraint in the lateral direction in repressing operation. This prevention of lateral flow is achieved by pressing the sintered preform inside close die. Repressing, otherwise known as coining often results in lower densities compared to closed die forging. This may be due to the incomplete closure of pores, especially those smaller pores which got rounded during the pressing process. Uniform and finer grain size is an added advantage of powder forging.

Numerous applications involving high stress or wear, such as connecting rods, gears, cams, main bearing caps etc used in automobiles are often powder forged products.

1.6 Deformation of porous preforms:

Plastic deformation behavior of porous preforms differs significantly from conventional wrought materials. Poisson's ratio of porous preforms is a function of density. There is volume change of the sintered preform during plastic deformation, unlike conventional materials. Similarly, the yield criterion for porous materials is also a function of density.
A simple yield criterion for porous materials has been proposed by Khun. It is given by:

$$[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2(\sigma_3-\sigma_1)^2}{2}+(1-2\nu)(\sigma_1\sigma_2+\sigma_2\sigma_3+\sigma_3\sigma_1)]^{1/2}$$

Plastic Poisson's ratio for sintered porous preforms in terms of preform density and theoretical density is given by the expression:

$$\nu=\frac{1}{2}(\frac{\rho}{\rho_{th}})^2$$

During axial deformation of a sintered porous cylinder, the axial strain varies with density of the deforming preform. The axial strain as a function of the instantaneous and initial densities of the sintered preforms is given by:

$$\varepsilon_z = -\ln[\frac{\left(\frac{\rho}{\rho_i}\right)^2(1-\rho_i^2)}{1-\rho^2}]^{1/2}$$

Note: The derivation of the above equation can be done starting from first principle, namely, equating the volume change (or density change) of the preform to the total strain of the preform:

$$-\frac{d\rho}{\rho} = d\varepsilon_z + d\varepsilon_r + \ d\varepsilon_\theta$$

We know that $d\varepsilon_\theta = \ d\varepsilon_r = \ -\nu d\varepsilon_z$

Substituting for $d\varepsilon_\theta$ and $d\varepsilon_r$ into the equation for density change, above, and also applying the plastic Poisson ratio expression given above, we get the required equation.

Infiltration: In this process, a molten low melting metal is made to flow into the pores of a porous metal by capillary action, so that the pores get filled. Copper is often used for infiltrating iron based porous alloys. Some of the bearings are formed by infiltration process. Similar process is oil impregnation of porous alloys for bearing applications. The evacuated porous alloy is immersed in oil so that the pores get impregnated with oil. Universal joints used in machines and automobiles are often made by this process in order to avoid application of grease lubricant.

Surface treatment can be done on powder metal parts in order to improve their surface wear resistance and hardness. One common process is steam treatment of the surface of sintered ferrous alloys. Exposure of the surface to steam results in formation of thin oxide layer on the surface, which imparts high surface hardness and wear resistance.

Example -1: Iron powders have particle density of 1.4 g/c.c. These particles are used for making a compact of diameter 32 mm and height 16 mm. If the theoretical density of iron is 7.85 g/c.c., calculate the volume of the compact.

Solution:

Volume of compact = 1286 cu.mm

Mass of iron powder corresponding to the compact volume = 7.85 X Volume = 101 grams

Volume of loose powders = 101/1.4 = 72.15 cu.mm

Pilgering, Semi-solid forming, SPD

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1.Quiz: .... Error! Bookmark not defined.

1.Pilgering, Semi-solid forming, SPD:

2.1 Pilgering:

Forming of seamless tubes is often performed by processes such as tube piercing, tube extrusion, plug rolling, Mannessmann process etc. In Mannessmann process, otherwise known as pierce rolling, the hot billet is drawn between two contoured rolls which are placed at an angle of 3 to 6 degrees with respect to the billet. The billet is bitten by the tapered rolls. Spiral movement of the billet against the piercing mandrel results in production of thick hollow tubular section.

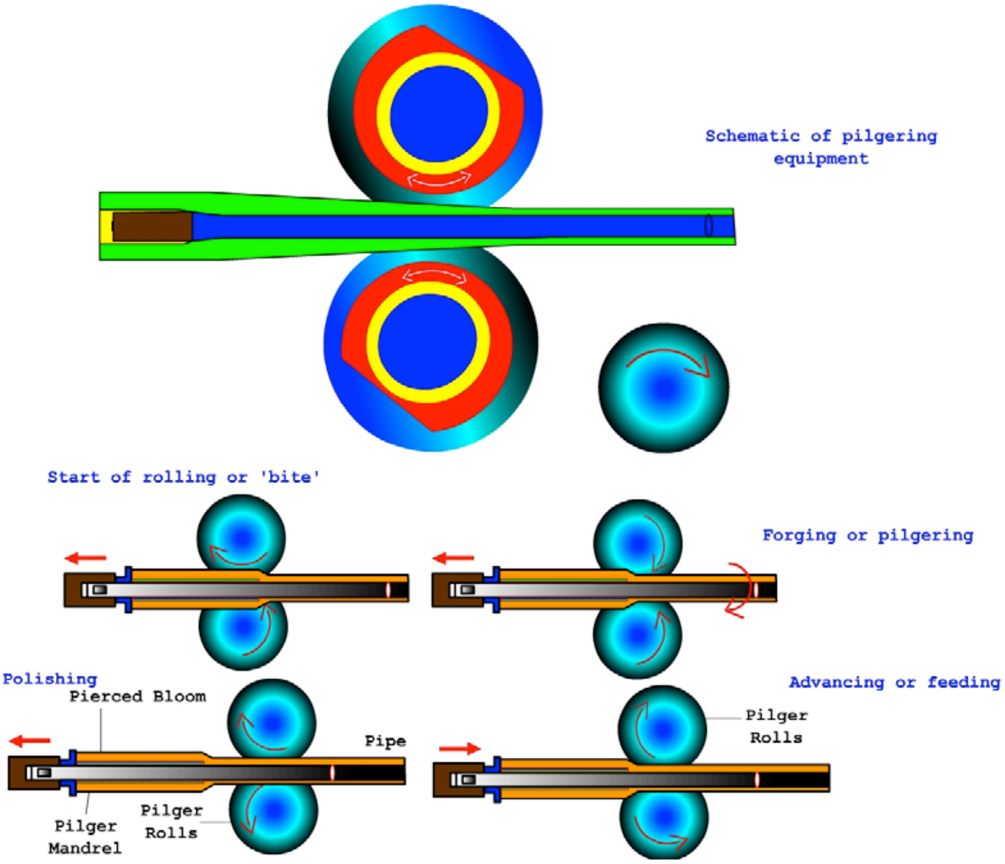

Fig. 2.1.1: Pilgerin process

The thick-walled tubes formed by the Mannesmann process are reduced in thickness and elongated in length by pilger rolling process, which is carried out hot. The wall thickness and diameter of the tube is reduced by a pair of grooved rolls and a piercing mandrel. The tube is moved back and forth repeatedly. The tapered mandrel affects reduction in diameter of the tube, while the grooved rolls reduce the thickness of the tube. After each pass, the tube is rotated through 30 to 90 degrees, which advances the tube. Pilgering results in smooth finish as well as high degree of accuracy.

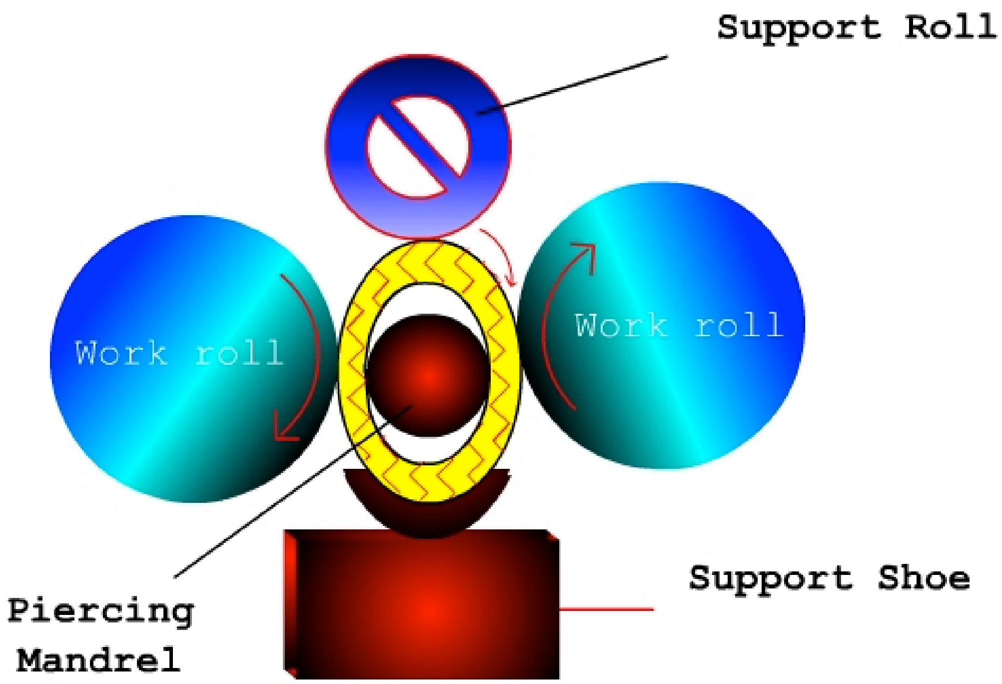

Fig. 2.1.2: Finishing operation on tube

2.2 Semisolid forming:

Semisolid forming is the process of forming materials in semi-solid state – mixture of liquid and solid phases. The metal is heated above the solidus temperature so that it melts martially. At this stage it is subjected to forging, casting, or other forming processes. The solid fraction may vary from 10% to 40%. Due to the high viscosity of the semi-solid mass, turbulence is not present during the processing. Therefore, voids due to entrapped gases are not present in the finished part. Intricate parts can be fabricated by this process. Shrinkage defects, characteristic of casting process are very less. It is also considered a net-shape forming process. Lower processing temperature of the semi-solid process improves the die life.

Thixoforging and extrusion is the forging or extrusion of the semi-solid mass into the required shape. The required forming loads are lower compared to the conventional forging or extrusion. Thixoforming of steels has been attempted but the difficulties involved in the process such as high thermal stress of the tooling continue to be the bottlenecks.

Processing steps involve production of billets with globular microstructure, reheating the billets to semi-solid condition using inductive heating and forming into final shape in a single step. Billets for semi-solid forming are often produced by direct chill casting with magnetohydrodynamic stirring to avoid dendritic grain formation. Quick reheating of the billet ensures avoidance of grain growth. The slurry is then thixocast or thixoformed. In thixoforging the semi-solid billet with 30% solid fraction is inserted into the lower die and the upper half of the die is closed in. Thixoextrusion involves squeezing of the slurry inside a closed die and a punch.

Typical applications of semisolid forming include automotive connecting rods, fuel rails, chassis parts, steering knuckles, pump housing, gears etc.

------------Diagrams

Fig. 2.2.1:

In rheoforming process, the metal is melted, cooled to a temperature above solidus temperature, maintained in semisolid state using heating inside a cup and transferred to the forming die. The dies are pre-heated to 300 degrees C and rinsed with argon gas. Upper die is usually fixed and the forming pressure is applied on the lower die. Holding pressure is applied on the upper die. After forming the part is ejected from the upper die.

2.3 Forming by Severe Plastic Deformation(SPD) processes:

According to Hall-Petch relation, fine grain size increases the strength and fracture toughness of materials. It also promotes superplastic behavior at lower temperatures and at higher strain rates. In conventional thermo-mechanical forming processes grain sizes above 10 micro meters are possible. If sub-micron or nano grain size are to be achieved, processes such as vapour deposition, ball milling, severe plastic deformation can be employed.

In severe plastic deformation, sub grain formation occurs at moderate deformations, followed by the formation of high angle grain boundaries under large deformation. This results in formation of nano grains. Under moderate deformations, low angle boundaries form. Subsequently, during severe deformation high angle grain boundaries form due to increase in surface to volume ratio and surface tension along grain boundaries. Grain boundaries become serrated. This is known as geometric dynamic recrystallization. Higher strain rates are required for affecting the formation of serrated grains which finally turn into sub-micron grains.

2.3.1 Equal channel angular processing:

Equal channel angular processing or equal channel angular extrusion process is the most popular SPD process. The ECAP die consists of two channels of identical cross-sections. The channels intersect at an angle of φ, which determines the severity of deformation. The angle φ usually varies between 60^o and 135^o. The channel intersection corner is rounded with an angle of ψ which varies from 0 to 90^o. The billet of circular or other symmetric cross-sections gets deformed inside the channel when pressed against the corner with a punch. Deformation of material is predominantly by shear along the direction parallel to the intersecting plane of the die channels. Material shear is concentrated within a narrow band around the corner of the channel. The dimension of the billet does not change after deformation as the channel has constant cross-section. Deformation of the billet can be repeated in several passes, by inserting the billet into the channel several times. Before each pass, the billet can be rotated by predetermined angles. Four routes are commonly employed during ECAP. Route A without rotation, Route – 180^o rotation after each pass, Route Bc – 90^o and

Route Ba - +90 and -90^{o} rotation. The equivalent strain on the billet per pass is a function of the channel angle and corner angle. It is given by:

$$\varepsilon_{eq}=\frac{1}{\sqrt{3\ [2\cot\left(\frac{\psi}{2}+\frac{\varphi}{2}\right)+\psi cosec(\frac{\psi}{2}+\frac{\varphi}{2})}}$$

During ECAP, grains get elongated in the shear zone. This is followed by breaking up of grains in cells (grain subdivision) during medium strain conditions. This evolves into high angle grain boundaries at high strains. A change in strain path by rotation of billet will result in breaking up of the fibrous structure into granular structure. After ECAP, the deformed material often attains high strength without loosing its ductility.

Some of the inherent limitations of the ECAP are: it is an intermittent process and can not be easily scaled up for industrial production. The volume of material that gets worked during the process is usually low – less than 30%.

----------Diagram

Fig. 2.3.1.1: The ECAP process-die arrangement

2.3.2 High Pressure Torsion (HPT):

Bulk materials with ultra fine grain structure can be produced by the bottom-up approach, such as high energy ball milling or by the top-down approach such as severe plastic deformation. Grain size in ultra fine grained material normally is less than $1\mu m$. High pressure torsion is another method of producing nano grained structure. The fundamental principle involved in HPT is that when a material, while being subjected to torsion, is also subjected to longitudinal compression, it will be able to withstand higher twisting loads without fracture. Hydrostatic stress introduced during deformation of a material is known to increase the ductility. Similarly, the axial compressive force could increase the ductility and hence the ability of the metal to undergo severe torsion. Angular displacements as high as 85o could be withstood by the specimen with compressive stress upto 6GPa. The strain involved in the HPT process may be as high as 7. Such severe strain could produce grain size of 100 nm or less.

The simple HPT process consists in applying high axial pressures – of the order of GPa on a disc shaped billet with the help of two anvils, which are coaxial. The lower anvil is slowly rotated while the billet is axially pressed. This produces the necessary torsion on the billet. The torsion strain is induced by the interface friction between the lower anvil and the billet. The shear strain on the material is given by:

$\gamma = \frac{2\pi r N}{h}$ (for small strains only)

where N is number of revolutions, r and h are the dimensions of the disk.

For large strains, the following expression holds good:

$$\varepsilon = ln[1 + (\frac{\varphi r}{h})^2]^{1/2} + \ln(\frac{h_o}{h})$$

The above equation includes the reduction in thickness of the disk.

There is a variation of shear strain from the surface to the center of the disk. Strain at the center is zero. As a result of this the microstructure produced by the HPT is heterogeneous.

Hipping

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Hipping **3**

1.1 The hipping process: 3

Hipping

1.1 The hipping process:

Hot isostaticpressing , otherwise called HIP ping is a high pressure, high temperature densification process employed for consolidation of metal/ceramic powders, cladding, densification of castings etc. Simultaneous application of pressure and high temperature will ensure removal of pores from the casting or densification of the porous part. HIP combines powder consolidation and sintering. It is carried out at temperatures in the range 0.5 to 0.7 times melting temperature of the powder material. The pressure employed ranges between 100 to 500 MPa, though 100 MPa is common.

Important equipment used for HIP are: a pressure vessel to withstand high pressure -it should be gas tight, a furnace for heating the powder – usually radiation heating or convection heating with graphite or molybdenum or nichrome as heating elements, pressurizing gas, namely, argon with gas supply equipment, vacuum and control systems.

In hipping, the powder particles are subjected to plastic deformation due to applicable of pressure. Powders get deformed along the surface of contact. Diffusion also contributes towards establishment of metallurgical bond between the particles. The powders also undergo creep deformation along the contact surface. Densification could proceed by a combination of plastic deformation of particles, creep of the particles and diffusion along the interface. Typical densification maps could be generated for a given material, which indicate the mechanism of densification. A pair of maps, based on constant temperature and constant pressure are shown below:

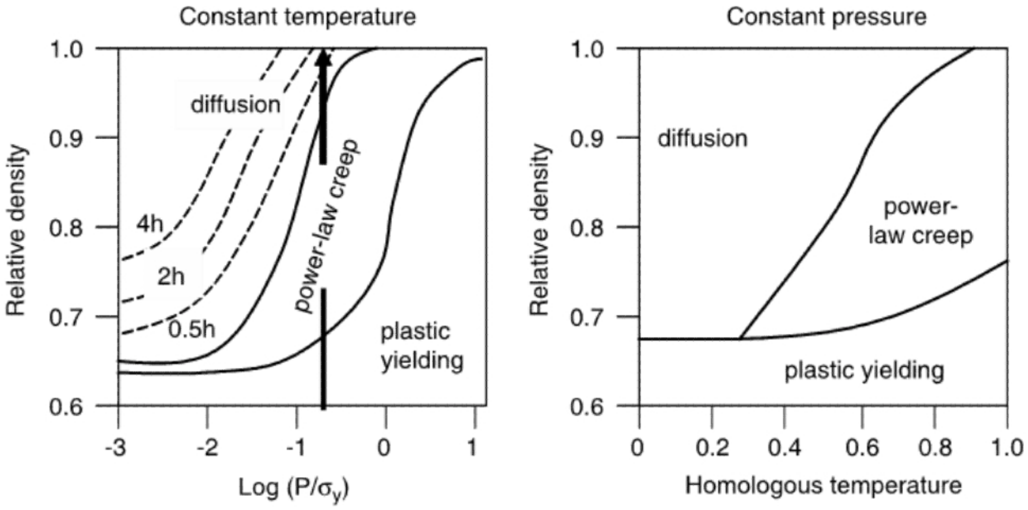

Fig. 1.1.1: Densification maps for hot isostatic pressing

The following diagram illustrates the hipping equipment. The furnace is kept inside a pressure vessel and the pressurizing gas, argon is supplied thorugh suitable supply system. Thermal insulation is provided on the outer side of the pressure vessel. The ends of the pressure vessel are closed by threaded arrangement. The powder to be consolidated is encapsulated in mild steel or stainless steel capsules.

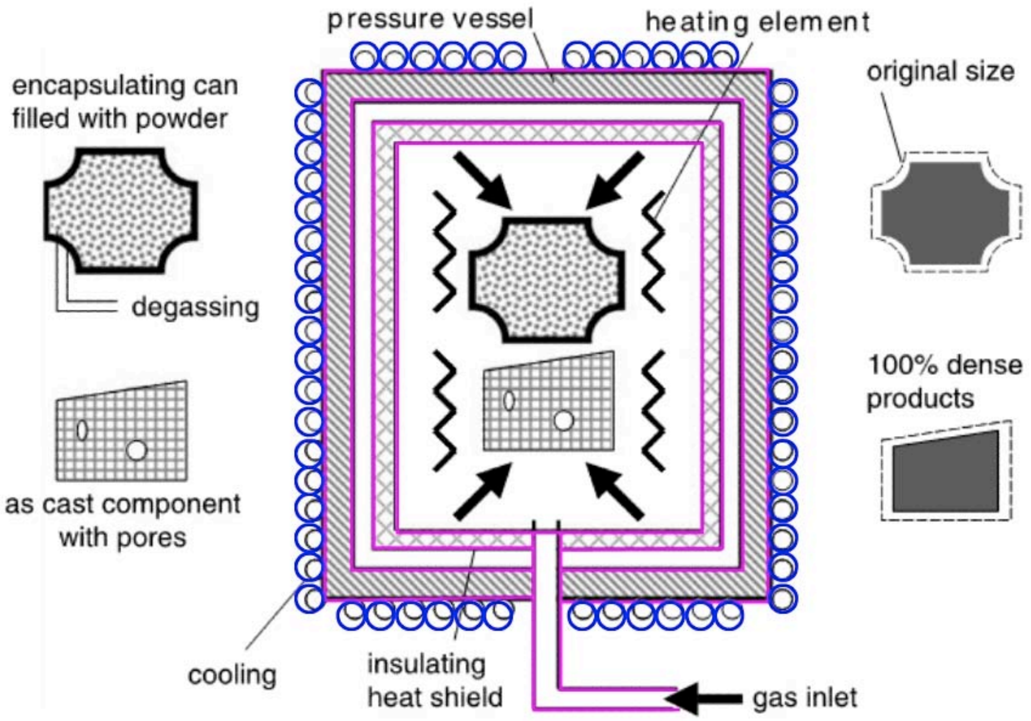

Fig. 1.1.2: Illustration of HIPping equipment

Hipping of ceramics powders or pre-sintered ceramics could produce 100% dense products. Hipping is employed for powders which are difficult to consolidate by conventional compaction and sintering cycles. Nickel based super alloys, tungsten based alloys, ceramics and tool steels are some of the materials, usually hipped, because of the difficulties involved in conventional methods like casting. Cladding of dissimilar materials could be effectively achieved through hipping. High pressure-induced plastic deformation ensures complete contact between parts to be clad.

Hipping of powder metallurgy parts is very a very important processing method as it can produce 100% dense parts with improved corrosion resistance, creep resistance and fatigue strength. Normally the density achieved in conventional powder material processing is never equal to 100%. Cemented carbide tools are made by hipping.

Some of the important factors governing hipping process are: powder characteristics, peak pressure and temperature, heating/cooling rates, cycle time, gas purity, etc.

Reactive synthesis of complex intermetallics or alloys could be done in hipping. Hipping can produce near-net-shape parts fully dense with uniform properties. Large components could be produced by hipping. Rarely, pot-hipping processing such as forging may be required for effective densification.

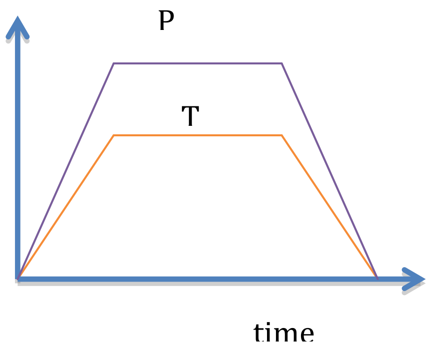

Fig. 1.1.3: Variation of hipping pressure and temperature during hipping cycle; P-pressure, T-temperature

Geometry of the deformation zone

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1.2 Effect of **Δ** on friction:.. 4

1.Geometry of the deformation zone

1.1 Deformation zone geometry parameter:

In the analysis of metal forming process, friction and shear deformation (redundant deformation) of material play notable role. Both factors contribute towards raising the forming load. Both of these factors are basically governed by the geometry of the deforming zone - shape, size of the zone of the material which gets deformed. The deformation zone is usually in the form of converging channel. In axi-symmetric extrusion, for example, it is in the form of a truncated cone. The shape of deformation geometry is known to affect the forming load as well as the final properties of the formed products.

The deformation zone geometry is defined by a parameter, Δ, which is defined as the ratio of the mean height or thickness to the mean length of the deformation zone.

$$\Delta = \frac{\overline{H}}{\overline{L}} \qquad 1.1$$

This parameter is related to another parameter called reduction, r. It is defined for plane strain deformation as: $r = 1 - \frac{h_f}{h_i}$. 1.2

For axi-symmetric deformation it is defined as:

$$r = 1 - \frac{{d_f}^2}{{d_i}^2} \qquad 1.3$$

The effect of Δ on the deformation pressure was considered briefly in module 2. In this lecture, we will consider effects of deformation zone geometry on other aspects of forming.

Recall that plane strain deformation refers to the condition where the strain of the material in one of the three principal axes is zero.

We can write down the expressions for Δ for both plane strain and axi-symmetric deformations as followed:

Consider plane strain extrusion in which a strip of initial thickness h_i gets reduced to a final thickness of h_f. Then the average height of deformation zone is given as: $\frac{h_i+h_f}{2}$. Similarly, the length of the deformation zone, from the geometry of the die, can be written as: $\frac{h_i-h_f}{2Sin\alpha}$.

Therefore, $\Delta = \frac{h_i+h_f}{h_i-h_f} Sin\alpha$ ---------- 1.4

Introducing : $r = 1 - \frac{h_f}{h_i}$, above, we get:

$\Delta = \frac{2-r}{r} Sin\alpha$ ------- 1.5 (for plans strain deformation such as extrusion)

Similarly, for axisymmetric extrusion or drawing, we take the diameters d_i and d_f, instead of the thickness. Therefore, we have:

$r = 1 - \frac{d_f^2}{d_i^2}$ --------- 1.6

Substituting 3 in I, we get:

$\Delta = \left(1+\sqrt{1-r}\right)^2 \sin\alpha/r$ ------------1.7

For strip rolling we can write down the deformation zone geometry factor as:

$\Delta = \frac{2-r}{r}\sqrt{\frac{h_i}{rR}}$ ----------- 1.8

Note that the parameter Δ decreases as r increases. Similarly, Δ increases as the die angle α increases.

1.2 Effect of Δ on friction:

It has been established that the ratio of frictional work to total work done in a forming process is inversely proportional to $\sin\alpha$. That is:

$\frac{w_f}{w_t} = \frac{m}{sin\alpha}$ ------------ 1.9

We know that Δ is proportional to sinα. Therefore, we can conclude that the frictional work is inversely proportional to Δ. A larger deformation zone geometry has lower friction and vice versa. In other words, if the height of deformation zone is larger, there is lower friction. With lower Δ, contribution of friction to the total work done in forming is larger.

1.3 Redundant work factor:

In order to account for the redundant shear deformation during forming, we can define the redundant work factor ϕ as:

$\phi = \frac{\varepsilon_r - \varepsilon_h}{\varepsilon_h}$ ------------1.10

whereε_r is redundant strain and ε_h is homogeneous strain. In wire drawing, for example, the factor is defined as:

$\phi = \frac{\varepsilon^*}{\varepsilon}$ -------1.11

whereε^* is the increased strain of a material subjected to redundant deformation, which otherwise would have undergone a yield strain of ε.

One can easily determine ε^* from the flow curve. Drawing the flow curve for the drawn wire and the annealed material, then shifting the flow curve of the drawn material to the right so that it merges with the flow curve for annealed metal, and obtaining the corresponding strain from the shifted curve. This gives ε^*. See diagram below.

In general, the parameter ϕ is a function of die angle as well as reduction. Therefore, it could be related to Δ as:

$\phi = A + B\Delta$ --------- 1.12

ϕ Increases with deformation geometry parameter, linearly.

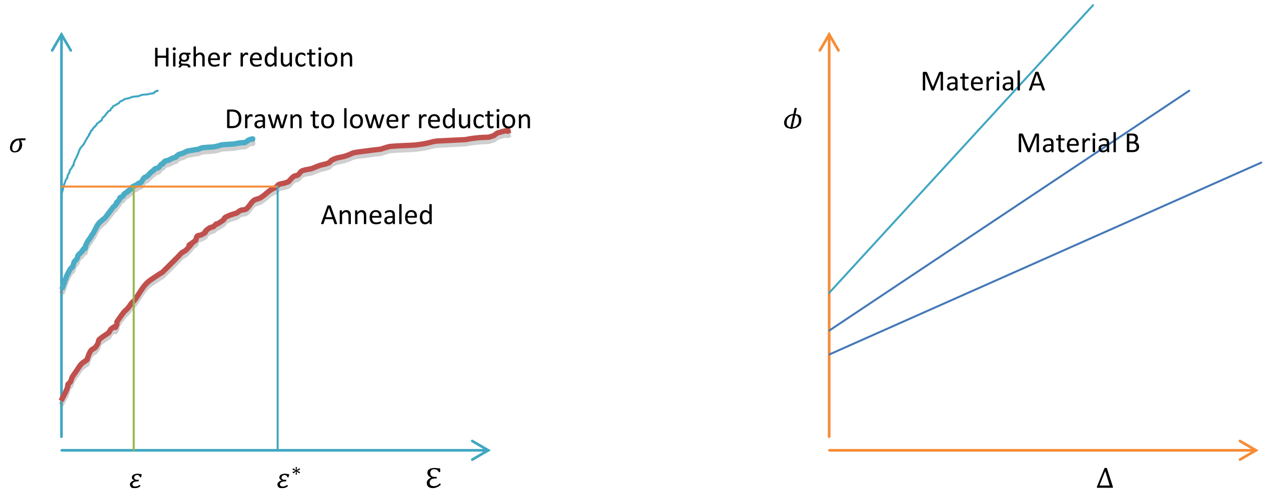

Fig. 1.3.1: Redundant work factor and deformation zone geometry

As seen from the diagram above, the redundant work factor increases with deformation zone geometry Δ. We also understand that as the die angle increases redundant deformation also increases – contribution of redundant work towards the total work of deformation is larger. Redundant strain is the shear strain of the material as a result of the changing geometry of the flow. Redundant deformation is found to be non-uniform in the deformation zone. Because of this non-uniform distribution, hardness within the deformation zone is found to vary between center and surface. The variation of hardness is expressed by a factor called inhomogeneity factor (IF).

IF is defined as: IF = (Hardness on surface – Hardness at center)/Hardness at center

IF is found to increase with increase in Δ. Further, IF is also found to increase with increasing die angle, α and decreasing reduction. Lower the reduction, higher the inhomogeneity factor. Inhomogeneity also introduces texture in the structure of the formed material. See diagram.

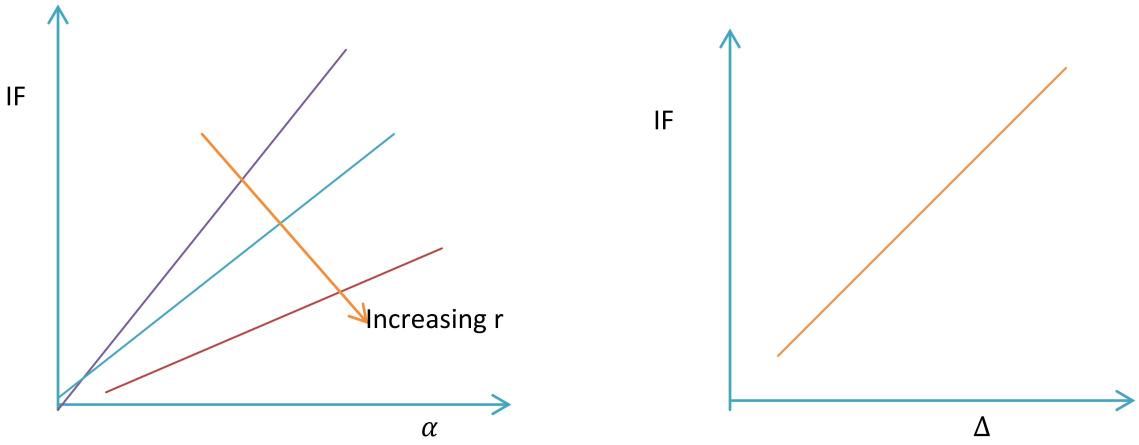

Fig. 1.3.2: Inhomogeneity factor versus deformation zone geometry and die angle

Inhomogeneity in the form of variation in hardness between center and surface is found to be larger for lower reductions in rolling. Lower reductions result in larger friction as well.

Yet another effect of the deformation zone geometry and die angle on is the density changes within the cross-section of the formed material. Larger Δ introduces high level of tensile stress – a kind of hydrostatic tensile stress at the center of the material. This causes center of the material to develop cracks and voids, which finally result in center cracks, chevron cracks in the drawn or extruded products. Larger die angle is also found to reduce density of the material at center compared to the surface. Such density variations are enhanced by the presence of inclusions such as oxides.

With larger values of Δ, residual stresses are induced in the material during forming. With large Δ the surface of the material is subjected to high tensile stress while the center is subjected to high compression. High Δ condition in rolling could cause the center of the material to split, causing allegatoring. Larger reductions introduce residual tensile stress on the surface, while smaller reductions could introduce surface compressive stress.

Workability

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1.Workability

1.1 Workability and processing map

Workability is a term related to bulk deformation processing of materials such as forging, extrusion, rolling etc. It refers to the ease with which a material could be formed without defects such as cracks. Formability refers to sheet metal processing. Ductility of the material is an important factor governing workability. High ductility material is expected to have good workability. Two factors are considered important while considering workability. One is the material factor – ductility, microstructure, grain size etc. The other factor is process factor – geometry of die, shape of material, friction etc.

Fracture of material during deformation is considered as the most important criterion for formability. Deformation is limited by fracture. High ductility will delay the fracture so that the material could be worked to greater levels of deformations. Fracture may occur on surface, or internally within the deforming material or it could occur at die-material interface. We have considered in earlier lecture how deformation zone geometry affects the internal fracture such as center burst.

Die contact surface cracks are primarily caused by excessive surface shear. Friction or low hydrostatic pressure can cause surface cracks. Surface cracks affect the surface finish. Extreme levels of tensile stress at center causes center burst or chevron cracks in extruded or drawn products. Sometimes we may have to change the deformation zone geometry to avoid such internal cracks. Defects in forging such as underfill, folds, laps, seams are found to be related to material flow. Improper material through narrow sections could cause defects on surface. Proper die design is necessary in order to eliminate the possibility of such defects. Flow – through defects are observed when material has difficulty in flowing through narrow sections because of chilling effect.

Metallurgical factors such as grain size, grain distribution also decide workability. In forming processes, one can control the grain flow, thereby enhancing the strength along the possible direction of loading. Fibrous structure is characteristic of most of the metal forming processes. In rolling for example grains become directional, thereby providing directional variation of properties (anisotropy). Workability is known to be reduced in case of coarse grained structure. Large grain boundary areas are more prone to cracks. Hot working increases the workability. However, hot forming may promote grain growth, which may coarsen the grains. In hot rolling of steel grain growth inhibiting elements such as titanium are added so as to promote fine grained structure after rolling. This increases the strength.

One way of evaluating workability is through processing map. A processing map specifies the regions of fracture and regions of safe forming for combinations of process parameters such as forming temperature, strain rate.

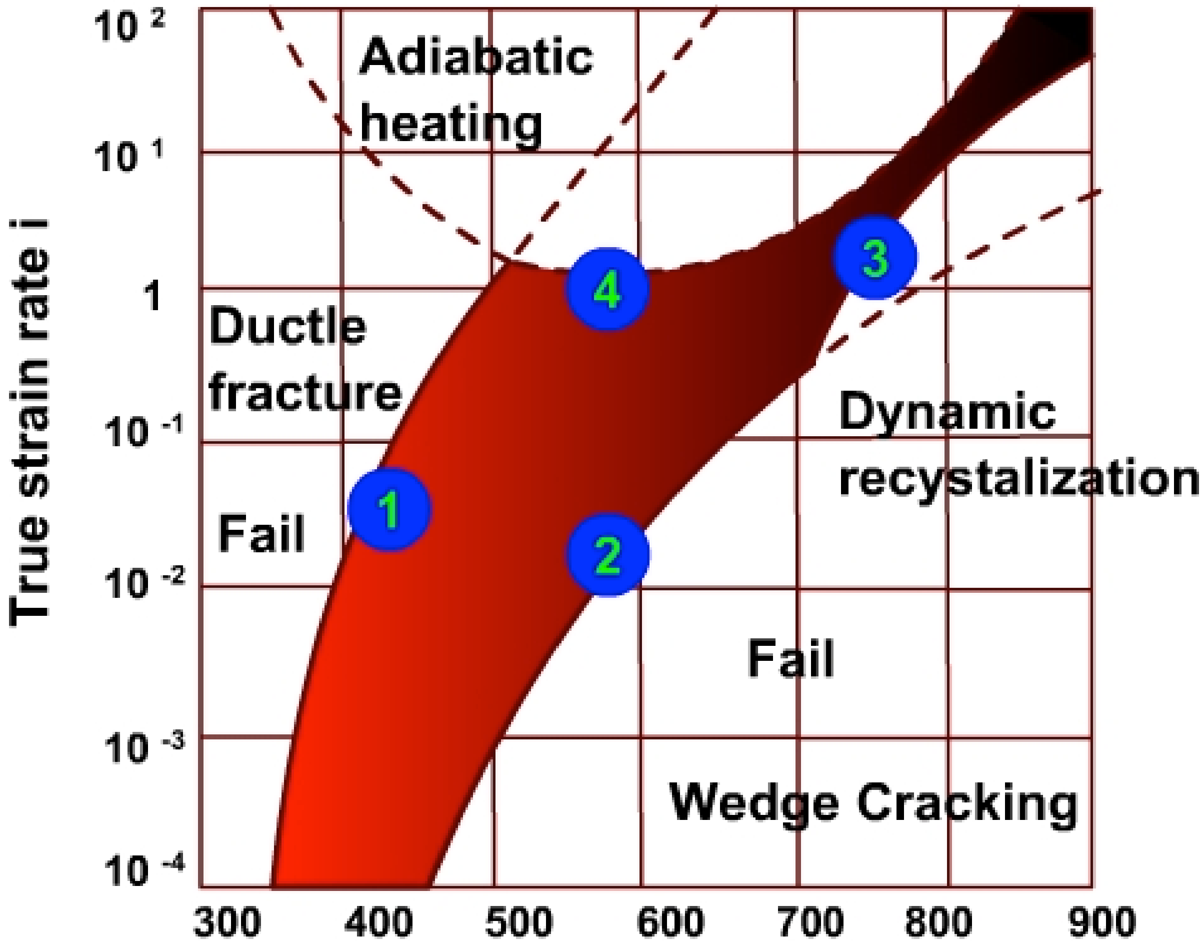

Fig. 2.1.1: Typical processing map. X-axis is temperature on degrees Celcius

From the map we understand that there is a maximum value of ductility corresponding to a given strain rate at a given temperature of working.

1.2 Metallurgical factors on workability:

Some of the metallurgical factors such as grain size, texture, strain hardening etc also contribute to workability. For instance, severe working may promote crystallographic texture, which leads to anisotropy. Shear bands may also form due to excessive working, due to plastic instability in compression.

In dynamic material model, the material flow stress is correlated with strain rate, temperature of working so that one can map the safe limit of working and limits of fracture under varying strain rate or temperature conditions. Strain rate sensitivity and temperature sensitivity of material are important in this method. The DMM model integrates flow stress, temperature, microstructure, with workability.

The parameter m, called strain rate sensitivity, given by:

$$m = [\partial(\log \quad)/\partial(\log \dot{\ })]_{,T}$$

governs the flow stress of a material.

Similarly, temperature sensitivity of flow stress is given by the parameter s, given by:

$$s = \frac{1}{T}\left[\partial \ln \quad / \partial(1/T)\right]_{\cdot,}$$

We expect m to be between 0 and 1. A high value of m means the onset of plastic instability and necking is delayed. A value of m near to unity may promote superplastic forming. Similarly, the value of s is dictated by entropy considerations.

Therefore, we have:

$$\partial s/\partial(\log \dot{\ }) < 0$$

High value of s means dynamic recrystallization occurs. Low value of s indicates that dynamic recovery is occurring. Dynamic recovery refers to formation of subgrain structure by cross slip of dislocations – a process of softening during hot working. Dynamic recrystallization also could cause softening.

High strain rates due to high values of s may cause adiabatic conditions which may create strain localization. This may lead to cracking.

1.3 Dynamic recovery and dynamic recrystallization:

Effect of strain rate on flow stress is more pronounced in hot working. Hot working considerably increases workability. During hot working the phenomena of dynamic recovery and dynamic recrystallization contribute to softening of materials. Dynamic recovery involves dislocation cross slip, annihilation of dislocations, and thereby the formation of sub grains. As a result the flow stress is considerably reduced. Uniform equiaxed grains form as a result of dynamic recovery.

Dynamic recrystallization tends to occur in materials which have high stacking fault energy. When the dislocation density increases to high levels, recrystallization is the only possibility through which the internal strains get relieved. High dislocation density and recrystallization could lead to internal cracks during forming.

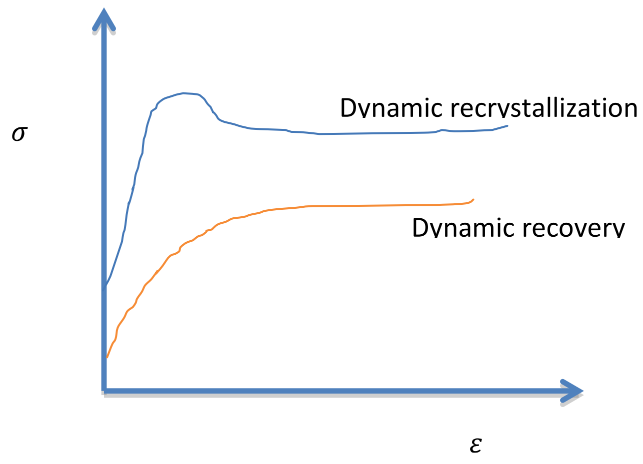

Fig. 1.3.1: Dynamic recovery and recrystallisation

Formation of dead metal zones in forming processes could lead to flow localisations. Friction and die wall chilling can also cause flow localisations. This affects the workability severely. Flow softening may also induce flow localisations. Flow softening is expressed by a parameter called flow softening rate, given as:

$$\gamma = \frac{1}{\sigma}\frac{d\sigma}{d\varepsilon}$$

The parameter α includes strain rate sensitivity factor and flow softening rate parameter, and is given by:

$$\alpha = \frac{\gamma - 1}{m}$$

If α is greater than 5 in compressive deformation, non-uniform deformation happens. Flow localization could also be caused by adiabatic heating conditions due to high strain rates of working of the material during hot working.

Workability of cast metals is generally poor. Therefore they are usually hot worked. Presence of low melting phases may cause localized melting, causing hot shortness. Wrought structure is found to enhance workability. In cold working, the material gets work hardened. Stresses are not relieved in cold working. Therefore workability is reduced. Hot working involves recovery process. Therefore workability is higher in hot working.

1.4 Stress state on workability:

It is recognized that hydrostatic state of stress could improve workability of materials. Extrusion is a process which can deform most of the materials because of the state of compressive stress involved. It is known that hydrostatic extrusion enables extrusion of brittle materials such as ceramics. Compressive stress is known to enhance workability. The mean or hydrostatic stress is given by:

$$\sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

A workability parameter β has been defined in terms of hydrostatic stress as followed:

$\beta = 3\frac{\sigma_m}{\bar{\sigma}}$ where $\bar{\sigma}$ is the effective stress. Variation of the workability parameter with strain to fracture is shown in figure below. The strain to fracture is higher for compressive stress state and lower for tensile stress state. Further, the diagram shows various forming processes superimposed in the curve. Wire drawing process, being a tensile deformation process, has lower workability. Extrusion process, being a compressive deformation has higher workability parameter.

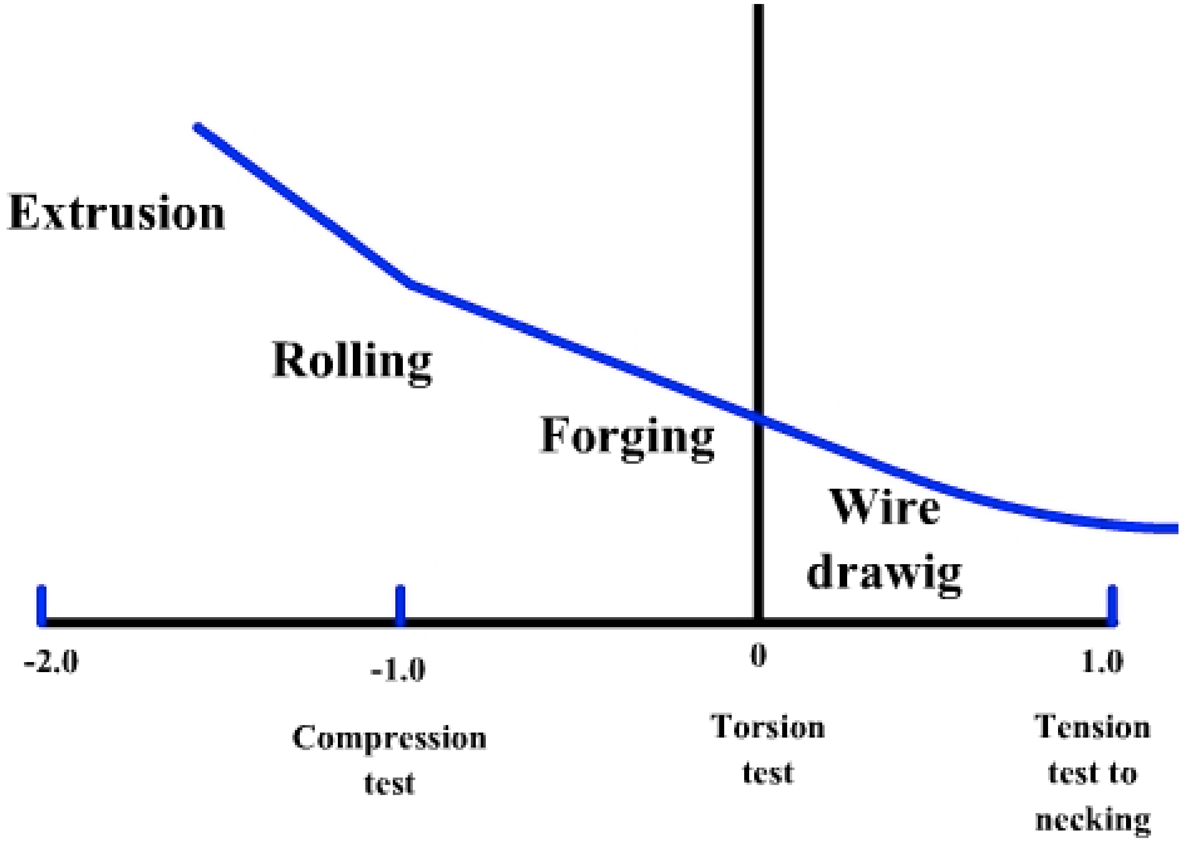

Fig. 2.4.1: Workability parameter

1.5 Fracture limit and workability:

There are several simple tests being used for determination of workability. The tensile test, Hardness tests, compressive test, hot torsion test, etc are commonly employed for determination of workability.

Workability is related closely to fracture. Fracture criteria will help us in predicting workability. There are two types of fracture, namely, ductile and brittle fracture. Ductile fracture is characterized by extensive plastic deformation before fracture, formation of voids and cavities. Localised necking could also happen. Brittle fracture is sudden and is not accompanied by any plastic deformation. One criterion for ductile fracture is given in the form:

$\int_0^{\varepsilon_f} \sigma^* \, d\bar{\varepsilon}$ = C

This states that fracture occurs when the strain energy per unit volume reaches a critical value C. We can also write:

$\int_0^{\varepsilon_f} \frac{\sigma^*}{\bar{\sigma}} d\bar{\varepsilon}$ = C

whereσ^* is the critical or the largest tensile stress locally acting, which causes the fracture, $\bar{\sigma}$ is effective stress. Fracture criteria in the form of correlation between the tensile and compressive strains corresponding to the condition of free surface cracks has been accepted as one of the easiest methods of evaluating fracture.

One of the important tests for workability is the fracture limit test, which correlates fracture with state of stress and frictional conditions. The fracture limit test is carried out using cylindrical specimen. Fracture limit line is established by conducting simple compression test on the cylinder under given condition of friction. The axial true strain is then plotted against radial true strain. For homogeneous deformation, the fracture limit line is a line with slope of -0.5. With interfacial friction between the cylinder and die the lateral surface of the cylinder undergoes bulging. Strains are measured at the instance of occurrence of cracks on the bulged surface. The height to diameter ratio of the cylindrical specimen is varied in order to obtain varied conditions of fracture. The test is done at increasing strain values in order to extend the range of strains. Flanged cylinder or tapered cylinder could also be used in the test in order to extend the strain range. Typical fracture limit lines are shown in diagram below. The curves above the -0.5 slope line correspond to bulged specimen. With bulging the curves have greater slope.

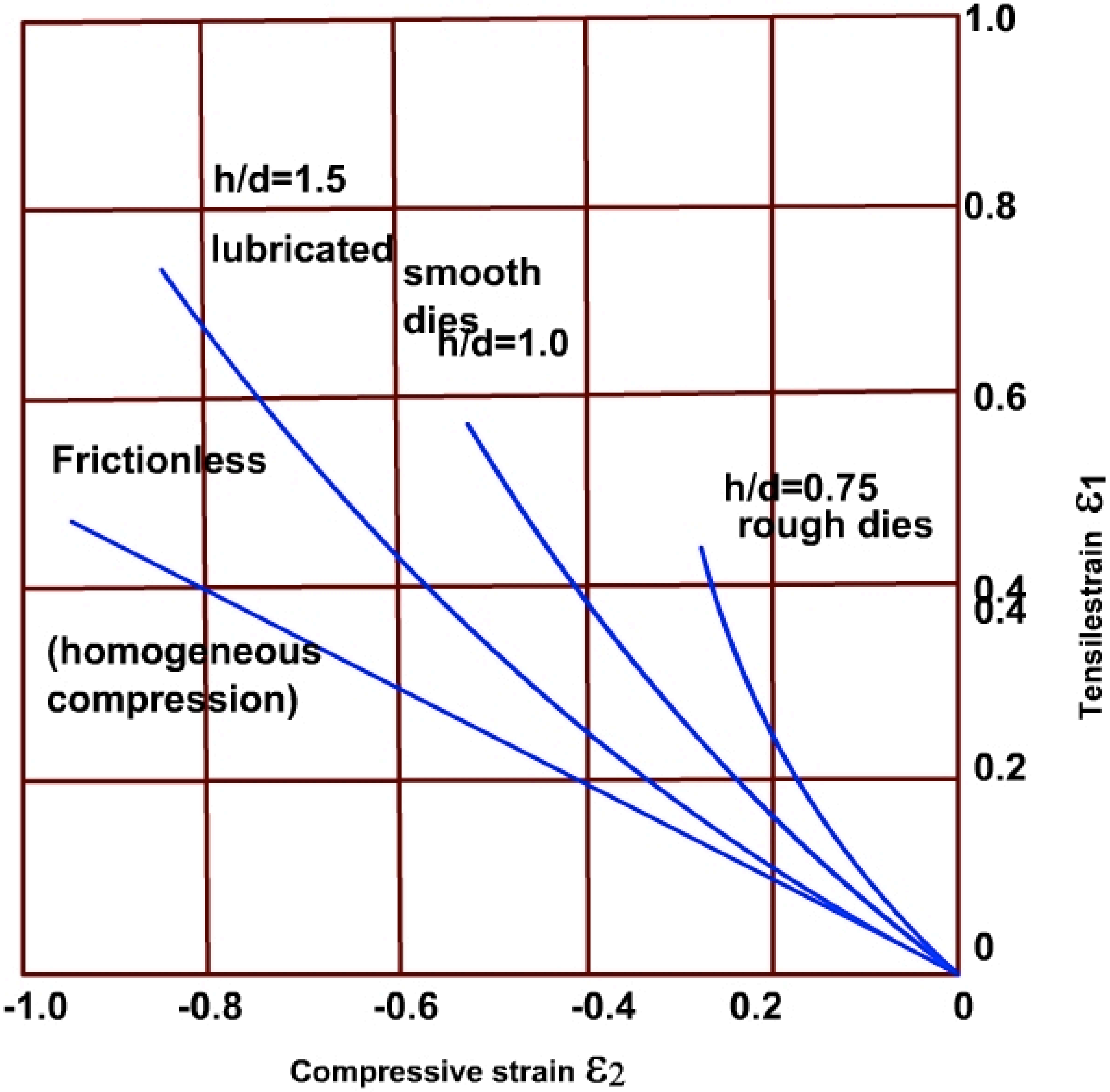

Fig. 1.5.1: Fracture limit curves

Application of fracture limit curve for workability can be understood from a simple illustration. Refer to the diagram given below: Consider the upsetting of a bolt head from a cylindrical rod of given diameter and height. To achieve a given strain given by: ln(d/D), different strain paths can be adopted depending on the condition of friction, work piece geometry etc. For two different materials the fracture limit lines are shown in figure below. The combination of material A and strain path a give the required strain without fracture. Material A with strain path b will not be able to produce the required bolt head without fracture. However Material B with strain path b could give a fracture free bolt head. The strain path b may correspond to a condition of poor lubrication – high friction, due to which bulging of free surface occurs.

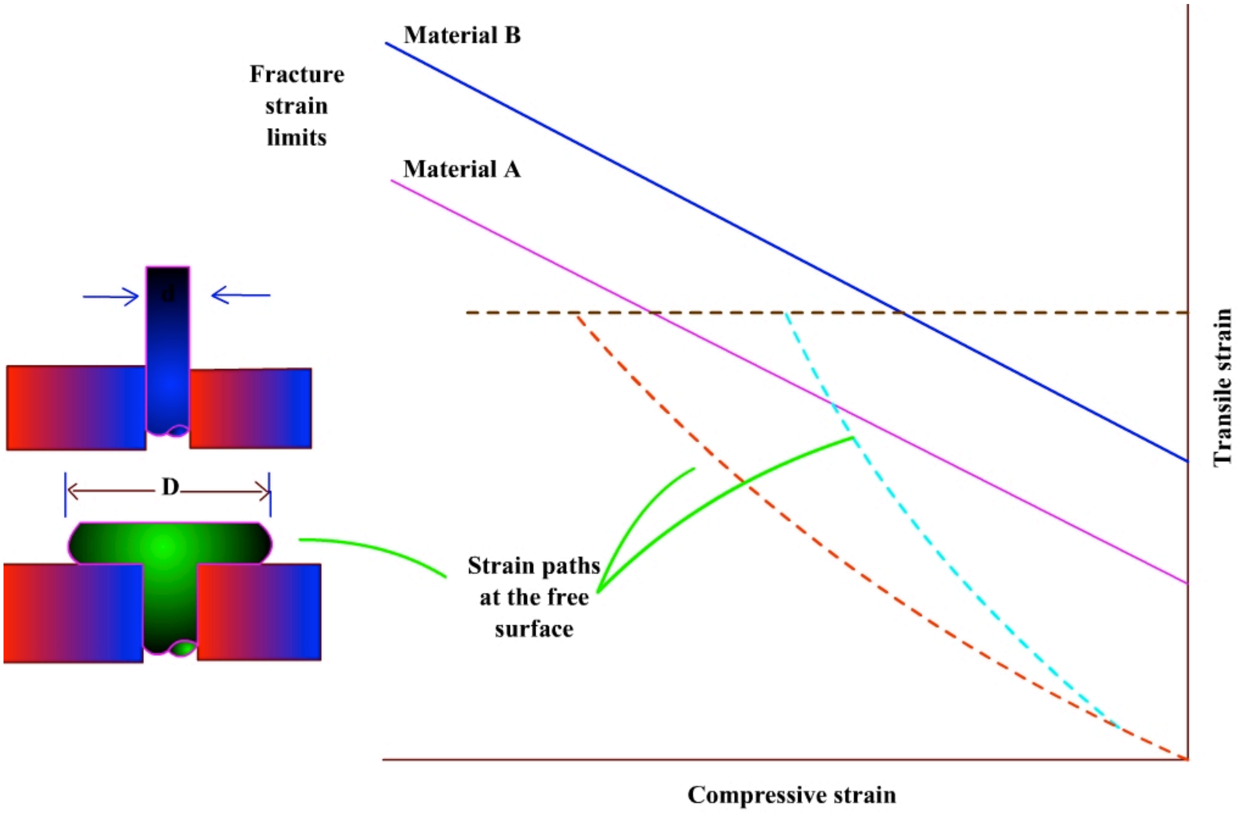

Fig. 1.5.2: Application of fracture limit criteria for upsetting a bolt head

In order to achieve the required amount of strain without fracture, we may look into other alternatives, namely, changing the die geometry, changing the preform shape, size etc.

1.6 The hot tension test:

In order to establish the upper and lower limits of temperatures for hot working, as well as determining the workability of materials at elevated temperatures, the hot tension test is performed. This test is carried out in a machine called Gleeble thermal simulator. The test specimen in the form of a cylindrical rod with a reduced diameter of 6.4 mm and overall length, including the button head of 89 mm is held horizontally, gripped with water-cooled grippers, heated resistively through the copper grippers. Thermocouples are embedded in the specimen for precise measurement of temperature. The amount of heating can be controlled by adjusting the electric power input to the specimen. Temperature, displacement, load are measured with respect to time. For constant cross-head speed, the strain rate gets reduced as the specimen elongates. However, at the instance of and after necking, there is increase in strain rate. The percent reduction in area of cross-section is calculated and is taken to be a measure of workability.

Qualitative rating of workability from the area reduction is given in table below:

Table 1.1: Workability for various forming processes

Reduction in area – hot tension test, %	Workability	Application
<30	Poor	
30 - 40	Marginal	Rolling, forging with light reductions
50 - 60	Good	Rolling, forging with normal reductions
60 - 70	Excellent workability, very little cracks	Rolling, forging – heavier reductions
> 70	Superior workability	Rolling, forging – heavier reductions

Formability

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1.Formability

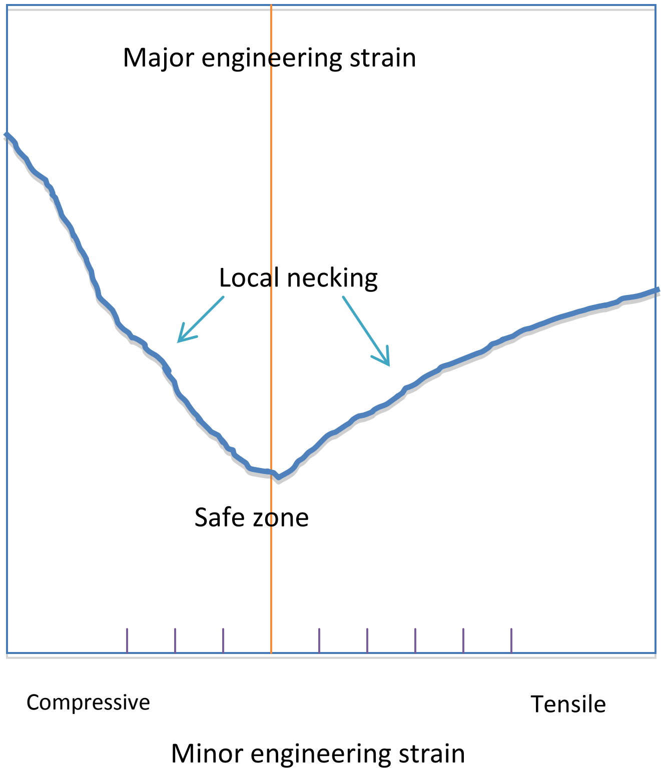
1.1 Introduction:

Formability is a term applicable to sheet metal forming. Sheet metal operations such as deep drawing, cup drawing, bending etc involve extensive tensile deformation. Therefore, the problems of localized deformation called necking and fracture due to thinning down are common in many sheet forming operations. Anisotropy also is a major concern in sheet metal operations. Formability is the ease with which a sheet metal could be formed into the required shape without undergoing localized necking or thinning or fracture. When a sheet metal is subjected to plane strain deformation, the critical strain, namely, the strain at which localized necking or plastic instability occurs can be proved to be equal to 2n, where n is the strain hardening exponent. For uniaxial tensile loading of a circular rod, the critical or necking strain is given to be equal to n. Therefore, if the values of n are larger, the necking strain is larger, indicating that necking is delayed. In some materials diffuse necking could also happen. Simple uniaxial tensile test is of limited use when we deal with formability of sheet metals. This is due to the biaxial or triaxial nature of stress acting on the sheet metal during forming operations. Therefore, specific formability tests have been developed, appropriate for sheet metals. Loading paths could also change during sheet metal forming. This may be due to tool geometry or metallographic texture.

1.2 Forming limit diagram(FLD):

Forming limit diagram is a very effective way of optimizing sheet metal forming. A grid of circles is etched on the surface of a sheet metal. Then the sheet metal is subjected to deformation. Usually the sheet is deformed by stretching it over a dome shaped die. Strips of different widths can be taken for the test, in order to induce uniaxial or biaxial stress state. The circles deform into elliptic shapes. The strain along two principal directions could be expressed as the percentage change in length of the major and minor axes. The strains as measured near necks or fracture are the strains for failure. A plot of the major strain versus minor strain is then made. This plot is called Keeler-Goodwin forming limit diagram. This plot gives the limiting strains corresponding to safe deformations. The FLD is generally a plot of the combinations of major and minor strains which lead to fracture. Combination of strains represented above the limiting curves in the Keeler-Goodwin diagram represent failure, while those below the curves represent safe deformations.

A typical Keeler-Goodwin diagram is shown below. The safe zone in which no failure is expected is shown as shaded region. Outside this zone there are different modes of failure represented at different combinations of strains. The upper part of the safe zone represents necking and fracture.



Strains above the curves result in failure.

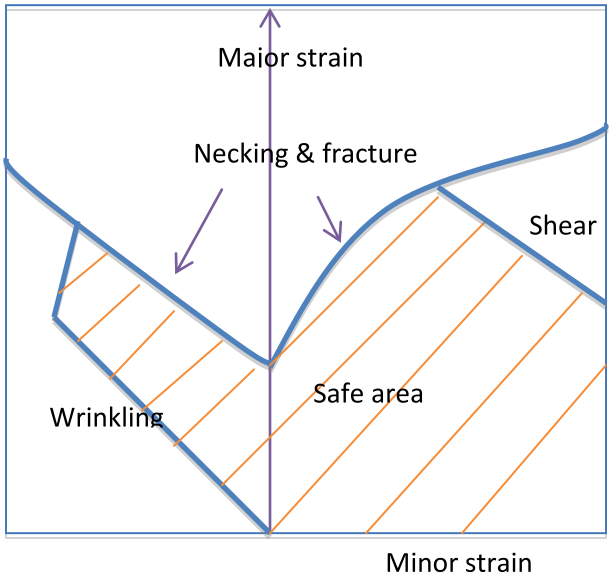


Fig. 1.2.1: Keeler-Goodwin diagram

The slope of the right hand side curve (necking curve) is found to decrease with increasing values of the strain hardening exponent, n. Similarly, variations in sheet thickness, composition, grain size all reduce the slope of the neck curve. The safe region is narrowed down by biaxial stress state. Sheet thickness also has effect on FLD. Higher sheet thickness increases the FLD.

3.3 Formability tests:

In cup drawing process, a formability parameter known as limiting draw ratio is very useful. LDR is defined as the ratio of the initial diameter to the diameter of the drawn cup. Many tests have been evolved for determination of limiting draw ratio of sheet metals. Cupping tests such as flat bottom test, hemispherical cup test and conical cup test are used for determining LDR. In swift cup draw test cups with flat bottom are drawn from circular blanks. Each time the diameter of the sheet is increased. The maximum diameter of the sheet which can be successfully drawn is determined, from which LDR can be found.

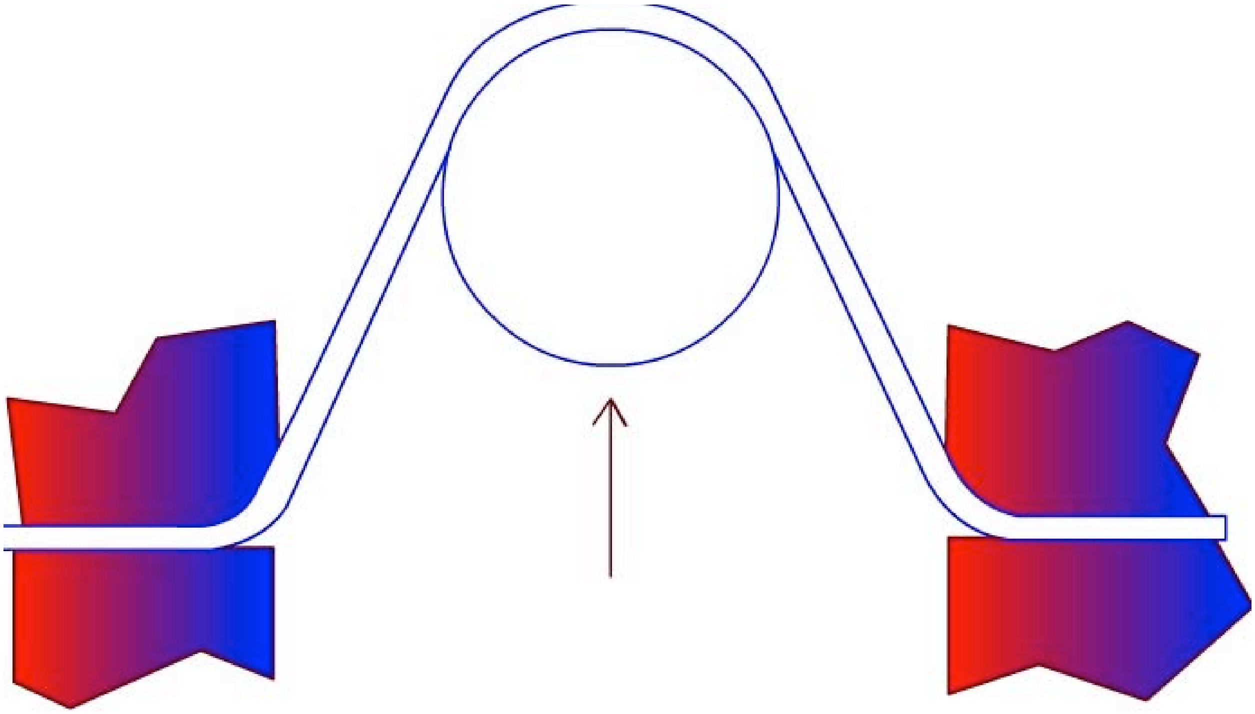


Fig.1.3.1: Schematic of Typical formability test for sheet metal

In Olsen and Erichsen test, the sheet is stretched over a hemispherical tool to form a dome cup shape. The height of the dome is considered as index of drawability. In Fukui test the sheet is both drawn and stretched over a cup of conical shape. Both drawing and stretching happen. The circular blank is drawn through a conical die with a circular punch without using a blank holder. The ratio of minimum diameter at which crack does not appear to the initial diameter of the blank is taken as a measure of formability of the sheet metal.

In another test known as OSU formability test, cylindrical punches of three different tip geometries are used to penetrate the sheet which is held clamped on both ends. One has to measure the height of the drawn part of the sheet at the instance of failure.

If larger strains are to be introduced hydraulic bulge test is the most appropriate. In this test, the sheet metal is subjected to oil pressure, after being placed on a circular hole and clamped. The oil pressure, radius of curvature of the sheet and radial strain are to be known in order to plot the stress-strain curve.

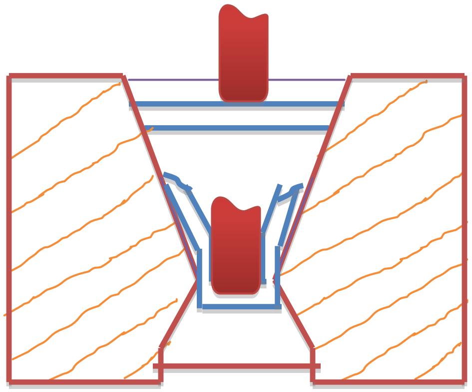


Fig. 1.3.2: Fukui Cup Drawing Test

The stress strain plots can be obtained after the test in order to understand the extent of strain undergone by the sheet before fracture. It is found that the strain rate sensitivity parameter m has effect on the uniform elongation after necking. Higher values of m promote larger uniform elongation after necking. It is also found that the cup height increases with higher strain hardening exponent. This is due to the delayed necking with higher strain hardening exponent values.

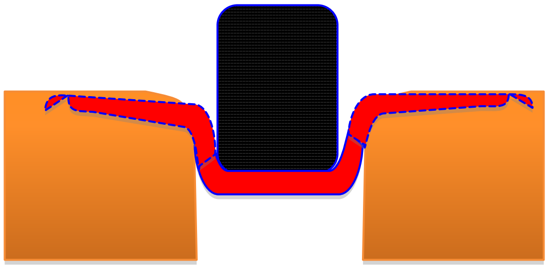


Fig. 1.3.3: Swift cup test

1.4 Anisotropy on formability:

In deep drawing of sheet metals, anisotropy of the material is known to be beneficial. Anisotropy is the variation in properties with respect to directions, due to variations in microstructures introduced in forming operations such as rolling. In rolling, the grains are elongated along the rolling direction. As a result, tensile properties differ along different directions. The rolled sheet can be subjected to uniaxial tensile test. The true strains along the thickness and width directions can be determined. If w is the width of the sheet and t is thickness of the sheet, the normal anisotropy R is defined as:

R = $\frac{\ln\frac{w_f}{w_i}}{ln\frac{t_f}{t_i}}$ = true width strain / true thickness strain of the sheet.

If R =1 then both height and width strains are equal – this corresponds to isotropic material. R also depends on orientation of the material with respect to the rolling direction. R can be estimated along the direction of rolling, angle of 0^o, at an angle of 45^o with respect to rolling direction and perpendicular to rolling direction. We can define the normal anisotropy as:

$\bar{R} = \frac{R_0+R_{90}+2R_{45}}{4}$

Note: A value of R = ∞ results if the thickness strain is equal to zero. This means there will be no thinning effect on a sheet subjected to tensile deformation. Therefore, in sheet forming, especially in deep drawing, we prefer high value of R (3 to 5) in order to ensure little thinning.

Similarly, the planar anisotropy is defined as:

$\Delta R = \frac{R_0+R_{90}-2R_{45}}{2}$

The normal anisotropy represents the average of anisotropy variation in all directions. The planar anisotropy gives the variation of anisotropy with direction.

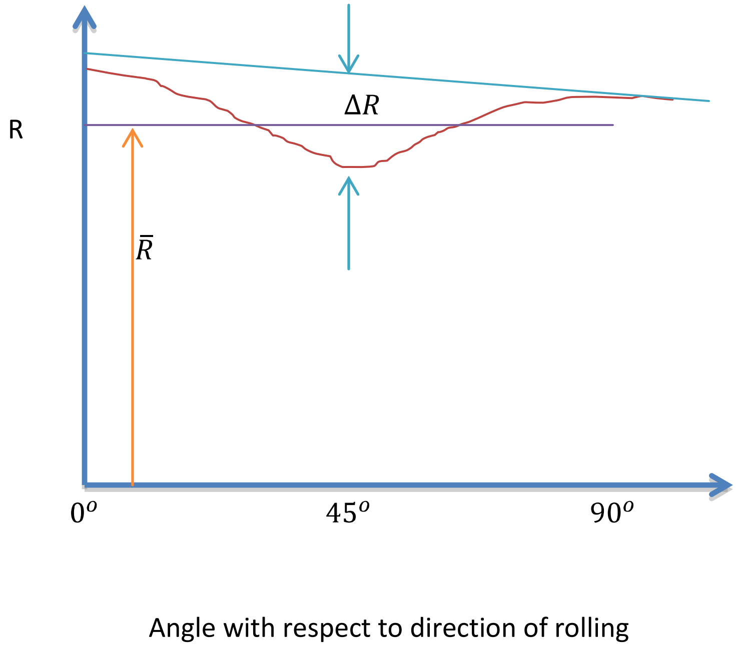


Fig. 1.4.1: Anisotropy in rolling

Figure above depicts the variation of anisotropy with respect to the direction of rolling. In deep drawing a sheet with higher anisotropy is preferred because the stress conditions in flange and the cup wall sections will be different. Cups with deeper walls could be drawn from materials with greater anisotropy. Further, with increase in normal anisotropy, the flow stress of the material decreases. Increased flow stress in the cup section of the deep drawn part, the strength of the cup section is increased. Therefore, formability of sheet metal in deep drawing can be said to be improved with increase in $\bar{R}$. However, an increase in planar anisotropy, ΔR is known to have a negative effect in deep drawing. Higher values of this anisotropy will introduce earing, a variation of the cup height around its wall circumference. In stretch forming the anisotropy parameter seems to be less significant. In deep drawing, the strain hardening exponent, n seems to be less significant.

Thermal effects and friction in forming

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1.Thermal effects and friction in forming

1.1 Temperature in metal forming

In cold forming operations, the energy supplied for deformation of metal is converted into heat inside the metal. Some of the heat may get dissipated through the surface. The metal undergoes rise in temperature as a result of energy accumulation. If overheating occurs, localized melting or grain boundary melting may occur. This will collapse the metal. Defects such as hot tearing may happen due to excess heating. Frictional heating also leads to increase in temperature of the work piece material.

Temperature of the work piece material during forming depends on several factors. Hot forming involves heating the work piece to high temperatures. The final temperature of the material can be given by the expression:

$T_f = T_i + \Delta T_d + \Delta T_f - \Delta T_c$

$\Delta T_d$is the increase in temperature due to deformation energy, ΔT_f is temperature rise due to friction and ΔT_c is the drop in temperature due to heat dissipation from the metal due to radiation, convection and conduction heat loss.

During deformation of a material, the amount of plastic work done per unit volume is given as $\bar{\sigma}\bar{\varepsilon}$. Of the total plastic work, $\bar{\sigma}\bar{\varepsilon}$ V, a small fraction, 5%, goes into formation of vacancies, dislocations in the microstructure. The remaining fraction, β or 95% of strain energy is stored as internal energy (m C ΔT_d) within the metal. Therefore we can write the temperature rise due to deformation energy as:

$\Delta T_d = \beta\bar{\sigma}\bar{\varepsilon}\, V / m\, C = \beta\bar{\sigma}\bar{\varepsilon} / \rho\, C$

where m is mass of work piece, C is specific heat capacity of the material and ρ is density.

The above expression is obtained by equating the fraction of stored internal energy to plastic work done. If strain rate is to be included in the expression, we can modify the above expression as:

$\Delta T_d = \beta\bar{\sigma}\dot{\varepsilon}\Delta t / \rho\, C$

whereΔt is time.

1.2 Frictional heating:

We know that the work done in overcoming friction between the die and work piece is given by:

$\dot{W}$f = Frictional shear force X velocity of flow X volume of work piece = τAvV = mkAvV

v is the velocity of deformation, V is material volume and A is area of contact between tool and work piece. We can equate the work done to rise in internal energy of the material due to frictional heating. It is given as:

mkAvΔtV = mCΔT_f

Therefore, ΔT_f = kAvΔtV / C = mkAvΔt / ρCV

K is the shear yield strength of the material.

We can now determine the temperature of the work piece as followed:

In hot forming, the work piece gets chilled out due to its contact with the cold die material. Heat loss from the work piece is assumed to occur by conduction and convection modes. The entire work piece is considered as a single lump with respect to the heat loss. The temperature of the work piece material at any instance is given by the expression:

$T(t) = T_i + (T_i - T_{die}) \exp(-\frac{ktA}{\rho CV})$

Ti is the initial material temperature.

We can now write the current material temperature as:

$T = T_i + (T_i - T_{die}) \exp(-\frac{ktA}{\rho CV}) + \Delta T_d + \Delta T_f$

This expression gives us the actual temperature of the work piece at a given instance, in terms of the heat dissipated, temperature change due to strain energy and friction.

1.3 Temperature measurements in forming:

Accurate measurement of temperature of the work piece and die materials during forming is important in order to estimate the forming load and other parameters. Temperature of exposed surfaces could be measured using radiation pyrometer if the die/metal temperatures are very high. The most popular method of measuring temperature is using thermocouples. Thermocouples with high sensitivity, such as Platinum-Rhodium thermocouples could be embedded in the die or work piece material. Time response of thermocouple should be as low as possible so that within the short duration of the forming process we could measure the temperature. Thermocouples could be inserted into bored hole inside the die and located at different places near the die surface. Transient temperature distribution on die surface during hot forming could be established using mathematical models for the heat transfer occurring on the surface of die. Finite element modeling could be employed for simulating the forming process as well as mapping the die/work piece temperatures.

Temperature of working is important from the point of view of flow stress, metallurgical structure and final properties of the formed product. Hot working is performed at temperatures above recrystallization temperature or above 0.5Tm. Tm is melting temperature. In hot working strain rate effects are more pronounced. The strain rate sensitivity parameter increases with temperature. Therefore, while performing hot forming, control of strain rate becomes important. Excessive strain rates may result in adiabatic conditions, leading to internal heating of work material. Excessive temperature rise may result in localized melting or hot shortness of work material. If on the other hand, slow rates of deformation are employed in hot forming, the material might cool down to temperatures lower enough to enhance the flow stress. As a result, the formed product could develop cracks and other surface defects. There should be a compromise between strain rate, temperature of working and working pressure in order to achieve a formed product without defects. Upper limit of forming temperature is based on surface oxidation, localized melting and hot-shortness. Lower temperature of forming is decided by the rate of recrystallization sufficient enough to avoid strain hardening. In hot forming, there is no work hardening due to recrystallization and recovery processes. Rapid cooling and fast working requires higher temperatures of working. Other factors such as dynamic recrystallization and dynamic recovery are also considered in hot forming.

The flow stress in hot forming is found to be complex function of temperature, strain rate. It can be given by the expression:

$$\sigma = A\dot{\varepsilon}^{m}e^{\beta/T}$$

In hot forming the flow stress of the material remains constant due to the fact that the work hardening effects due to dislocation motion are countered by recovery and recrystallization.

1.4 Friction in forming:

Friction arises between two surfaces in contact as a result of interlocking of the asperities. Asperities are microscopic valleys and depressions on surfaces. Friction between the tool and work piece surfaces plays considerable role in forming. First, friction enhances the forming load. Second, it leads to poor surface finish on the formed part. Third, it leads to considerable increase in temperature-frictional heating. Die life is reduced due to friction. Friction also results in non-homogeneous deformation of the material during forming. Therefore, friction has to be understood and ways of reducing it have to be devised if forming loads are to be reduced.

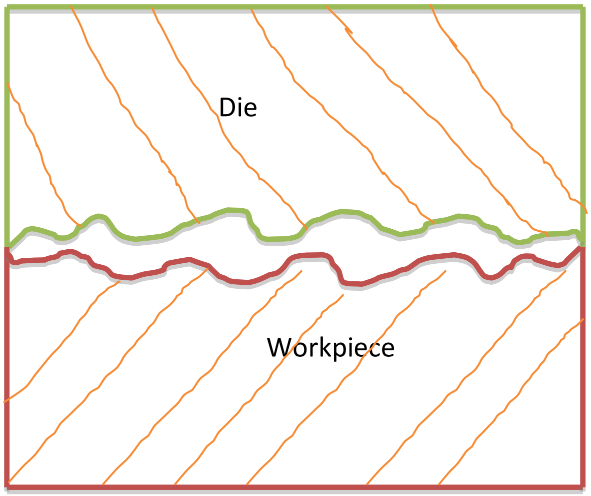

Fig. 1.4.1: Asperities on surfaces of two contacting objects

There are two types or models of friction identified in forming. Coulomb friction model is applicable for sliding friction. Two surfaces in sliding contact can be modeled by the Coulomb model. This model is most appropriate in forming operations such as rolling, drawing, sheet forming etc in which the normal pressure/stress is lower than or equal to the material flow stress. According to this model, the frictional shear stress is related to normal pressure by the relation: $\tau = \mu p$.

In forming processes such as closed die forging, extrusion the normal pressure is considerably greater than the flow stress. As a result, the friction at the contact surface can be said to be sticking friction. This model is called Tresca model. The frictional shear stress at interface can be taken to be proportional to the shear yield strength of the material (k). We can write, for Tresca model: τ = mk.

According Coulomb's friction model, the friction force is proportional to normal reaction force. Therefore, we have: μ = F/Fn. $\mu$is called coefficient of sliding friction or simply coefficient of friction. It appears from the expression: $\tau = \mu p$ that the coefficient of friction is dependent on normal pressure. This gives a misleading idea about μ.

According to Tresca model of friction we can write: $\tau = mk$, where m is called friction factor. M varies between 0 and 1. If m =1 we have the interfacial shear stress equal to the shear yield strength. In such a situation, we have sticking friction. The surfaces get interlocked with each other so that they could not slide against each other. Material beneath the surface undergoes shear deformation. The die material should not deform plastically and the work material could undergo plastic deformation. Sticking friction could happen at normal stresses greater than the flow stress by at least a factor of 3. Under the circumstances, the soft work material penetrates into the surface of the die material.

According to Coulomb model, the frictional stress increases with coefficient of friction, as the shear force is proportional to normal pressure. According to Tresca model, the frictional shear force is independent of the normal pressure, because, the shear stress is proportional to shear yield strength, which is a constant. In mixed mode of friction, both Coulombic model and Tresca model could happen simultaneously. It has been experimentally verified that when a cylindrical work piece is upset, along the outer circumference there is sticking friction, and inside – towards axis of forming there is sliding friction. This can be due to the runout of the lubricant and hence the metal-to-metal contact along the periphery.

1.5 Lubrication:

In order to avoid direct metal-to-metal contact we have to introduce a lubricant at the interface. The normal pressure or the shear stress will be transferred to the thin lubrication oil film. The oil film will support the normal pressure.

Dry friction is supposed to happen when the two surfaces are in direct contact. In this case, the oxides of the two surfaces are in direct contact. If the surface of a metal is exposed to atmosphere, it immediately forms a layer of oxide. The oxide layers may or may not act as lubricants. Therefore, dry friction is to be avoided in forming. The two oxides formed on the two surfaces may differ from each other, in terms of strength. This is due to the fact that each metal may have differing oxidation characteristics.

Hydrodynamic lubrication involves the separation of the two surfaces with the help of a thick film of lubricant. This kind of lubrication is common in extrusion, drawing, deep drawing, rolling etc. When the lubricant is drawn into the wedge shaped gap between the die and workpiece, and when the die or work piece move fast, the lubricant forms a thick film with sufficient pressure to separate the die and work piece surfaces. High forming velocity is required for hydrodynamic or thick film lubrication. Thick film lubrication is sometimes undesirable. It reduces the surface finish-surface appears rough and matt finish like. Thin boundary lubrication is preferred for good surface finish with shiny surface.

Boundary lubrication involves the formation of a thin film of lubricant which separates the surfaces. In this type of lubrication, the load is uniformly transferred from die to work surface. Moreover, higher loads can be transferred across the film. The net result is good surface finish and uniform surface deformation. Therefore, for metal forming thin film lubrication is most desirable. Lubricants such as stearates, contain polar molecules which react with the surface oxides and establish strong bonding. This increases the shear strength of the film, thereby preventing metal to metal contact. Fatty acids, compounds of phosphorous and sulfur are also used as lubricants for boundary lubrication. Solid lubricants such as graphite, molybdenum di sulfide form shear layers, which can provide the lamellae aligned parallel to the surfaces. Molten glass is used as lubricant for hot forming such as hot extrusion. Other lubricants include boron nitride, Teflon, calcium fluoride, cerium fluoride and polyethylene. Lubricant absorption on surface could be improved by phosphate treatment of steel surfaces. In cold extrusion of ferrous materials, phosphate coating is used a carrier of lubricant. For some alloy steels oxalate coating is preferred. For hot extrusion of non-ferrous alloys, graphite or lube oil are used as lubricant. Hydrodynamic lubrication is used during wet drawing of wires, in which the wire is dipped in a liquid lubricant container before drawing. The lubricating oil sticks to the surface of the wire. Due to high speed, the oil is hydro-dynamically drawn into the die and forms a film.

1.5.1 Contact stress measurement:

Contact stress between die and work piece can be measured using pins inserted in dies. Holes are made on the die surfaces, extending down through some dept. Pins ate inserted inside the holes, one pin perpendicular to the die surface and another one inserted at an angle. The other end of the pin inside the hole is provided with a force transducer. Transducer can measure the normal force and hence normal stress acting on the pin which is orthogonal to die surface. The inclined pin will sense the force exerted from which one can deduce the shear stress. Friction stress can also be measured using the pins.

1.5.2 Measurement of friction coefficient:

Conventionally, friction coefficients or friction factor could be estimated using the ring compression test. The ring compression test was described in one of the earlier lectures. Here we will try to understand one of the modern methods of measuring coefficient of friction – the pin-on-disk test. This method is quiet suitable for measuring sliding friction and friction coefficient – under lubricated or dry conditions. In this simple test, a pin shaped specimen is held against a rotating hardened disk, by applying a constant normal load. Using a cantilever and load cell arrangement, the friction force is measured. A data logging arrangement will plot the variation of coefficient of friction with respect to time duration of the test. Each time friction force acts on the cantilever the force is measured by the load cell. The test can be conducted with lubricant supplied at the pin-disc interface in order to characterize the lubricant.

$$\mu = F/N$$

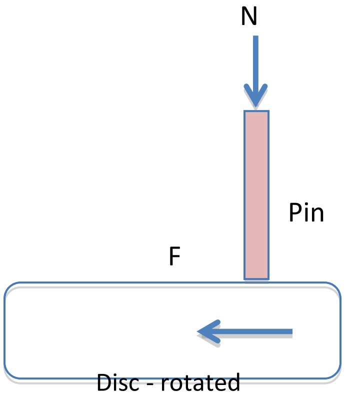

Fig. 1.5.2.1: Pin-on-disk test

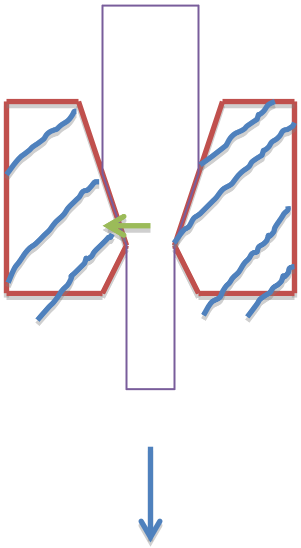

Fig. 1.5.2.2: Friction measurement in drawing

For measuring the coefficient of friction under sliding – for example the sliding of a sheet metal between die surfaces a simple strip draw test can be used. In this test, the strip made from the test material is pulled through a pair of die blocks. The die blocks are held together by applying a lateral force. The force on the strip in order to draw it is measured. The ratio of this force / reaction force is the friction coefficient. In order to find the friction coefficient in drawing or extrusion, we can pass the strip or wire through a conical die or a pair of inclined dies. The force for drawing or extrusion and the force for die separation are measured. From this the coefficient of friction is can be determined.

Typical friction coefficient values in forming:

Cold forming:

Material	Rolling	Extrusion	Forging
Stainless steel	0.06 – 0.1	0.05 – 0.1	0.05 – 0.1
Aluminium	0.03 – 0.06	0.05 – 0.1	0.05 – 0.07
Mild steel	0.05 – 0.1	0.05 – 0.1	0.05 – 0.1