CRYOGENIC ENGINEERING

Prof. Milind D. Atrey

Department of Mechanical Engineering,
IIT Bombay

Lecture No - 5

Earlier Lecture

- Introduction to Cryogenics
- Cryogens, Properties, T – s diagram
  - Argon
  - Air
  - Nitrogen
  - Oxygen
- Hydrogen
- Helium – Superfluid and its effects

Outline of the Lecture

Title : Material Properties at Low Temperature

- Structure of matter
- Stress – strain relationship
- Mechanical properties of Metals and Plastics at low temperature

Introduction

- Properties of materials change, when cooled to cryogenic temperatures.

- For example:

  - Rubber when quenched in LN_2, it turns hard and breaks like a brittle material.

  - Wires made of materials like Nb – Ti, exhibit zero resistance when subjected to LHe temperatures (Superconductivity).

Introduction

- The above examples show that material becomes hard and brittle at low temperature.
- The electrical resistance decreases as temperature decreases.
- Hence, a knowledge of behavior and properties like strength, ductility, thermal and electrical conductivities etc. of materials is necessary for the proper design.

Structure of Matter

- Solids are composed of atoms, which are bound together and are arranged in regular arrays.

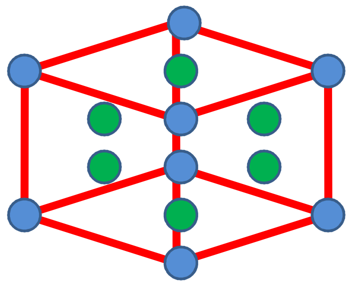
- Solids are broadly classified into two types
  - Metals
  - Non – metals
    - Plastics
    - Glasses

From Cryogenics perspective

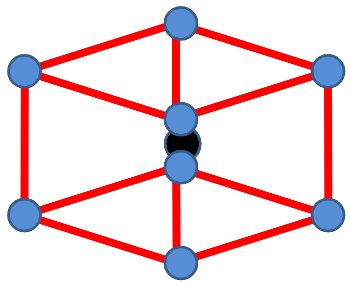
Metals

- Metals have a highly ordered structure.
- The atoms are arranged in symmetrical crystal lattices.
- Most common of these lattice structures are
  - Face-Centered Cubic (FCC)
  - Body-Centered Cubic (BCC)
  - Hexagonal Close-Packed (HCP)

Lattice Structure of Metals



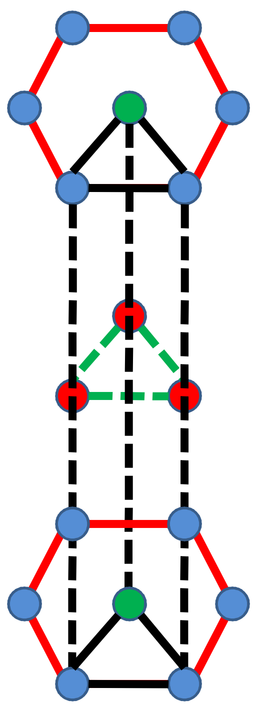
- **Face-Centered Cubic (FCC)**
  - An atom at each of the eight corners and an atom at the center of each of the six faces. (Total = 14 atoms).



- **Body-Centered Cubic (BCC)**
  - An atom at each of the eight corners and one atom at the center of cube. (Total = 9 atoms).

Lattice Structure of Metals

- **Hexagonal Close-Packed (HCP)**
  - An atom at each of the twelve corners, an atom at the center of each of two vertical hexagonal ends and three atoms in way between the ends of prism. (Total = 17 atoms).



  - The above lattice structures decides the number of slip planes in the crystal.
  - Slip planes are the directions within the crystal in which the planes can slip or move easily one over the other.

Slip Planes

- Real crystals do not have perfect lattice arrangements. There exists always some dislocations due to some imperfections.

- The number of slip planes governs the movement of dislocations and this governs the ductility and the impact strength of any material.

- The FCC structure has maximum number of slip planes, while the BCC has the least. The HCP structure falls in between the above two lattices.

- As a result, the FCC solids are more ductile than the BCC and the HCP.

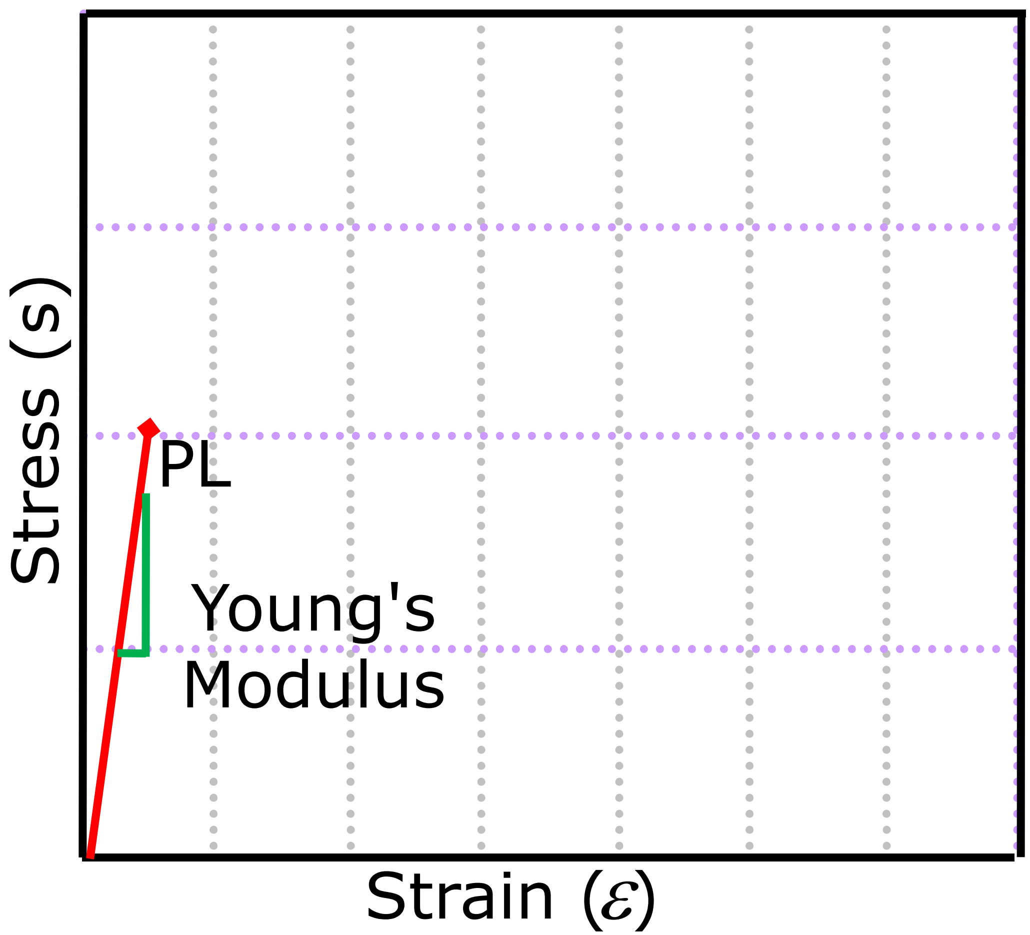
Properties of Materials

Sr. No.	Property
1	Mechanical
2	Thermal
3	Electrical
4	Magnetic

From Mech Engg. perspective

From SC perspective

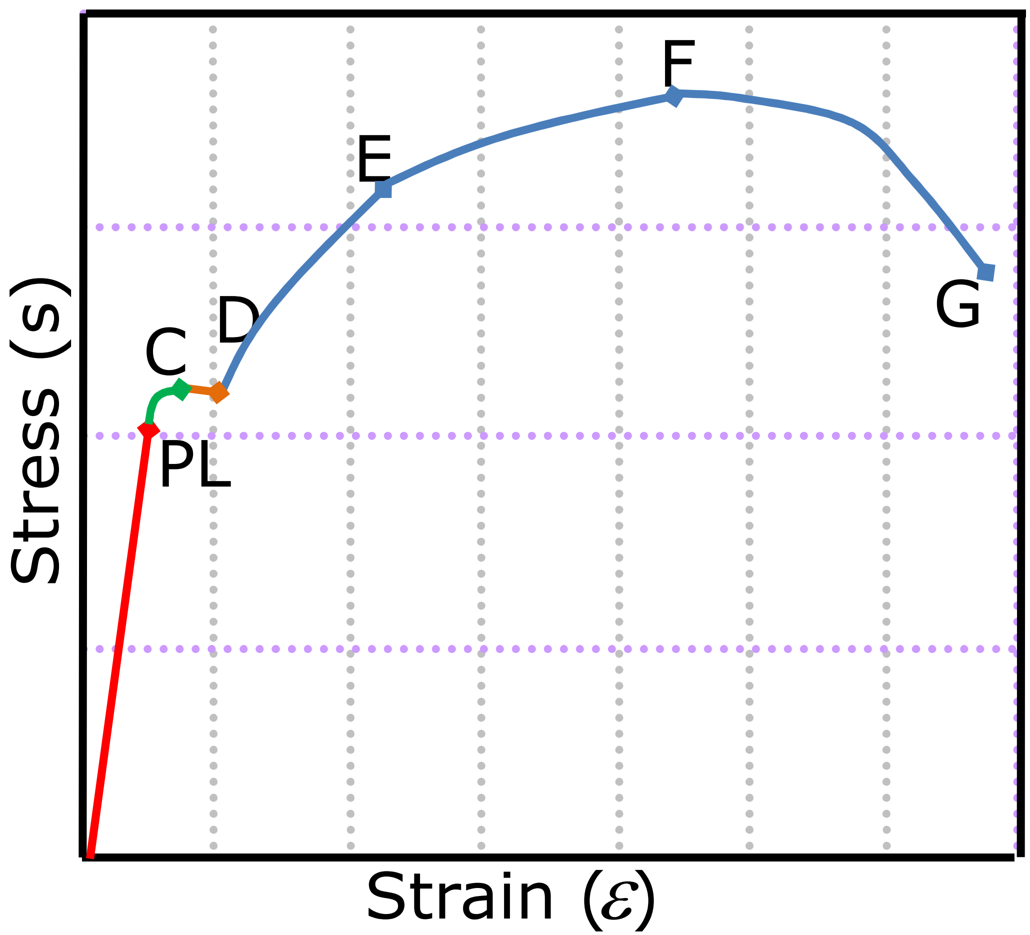
Stress – strain curve



- When a ductile specimen is subjected to a tensile test, the stress – strain relationship is developed as shown.

- Proportional Limit (PL) is the limit in which the elongation of the specimen is directly proportional to stress applied.

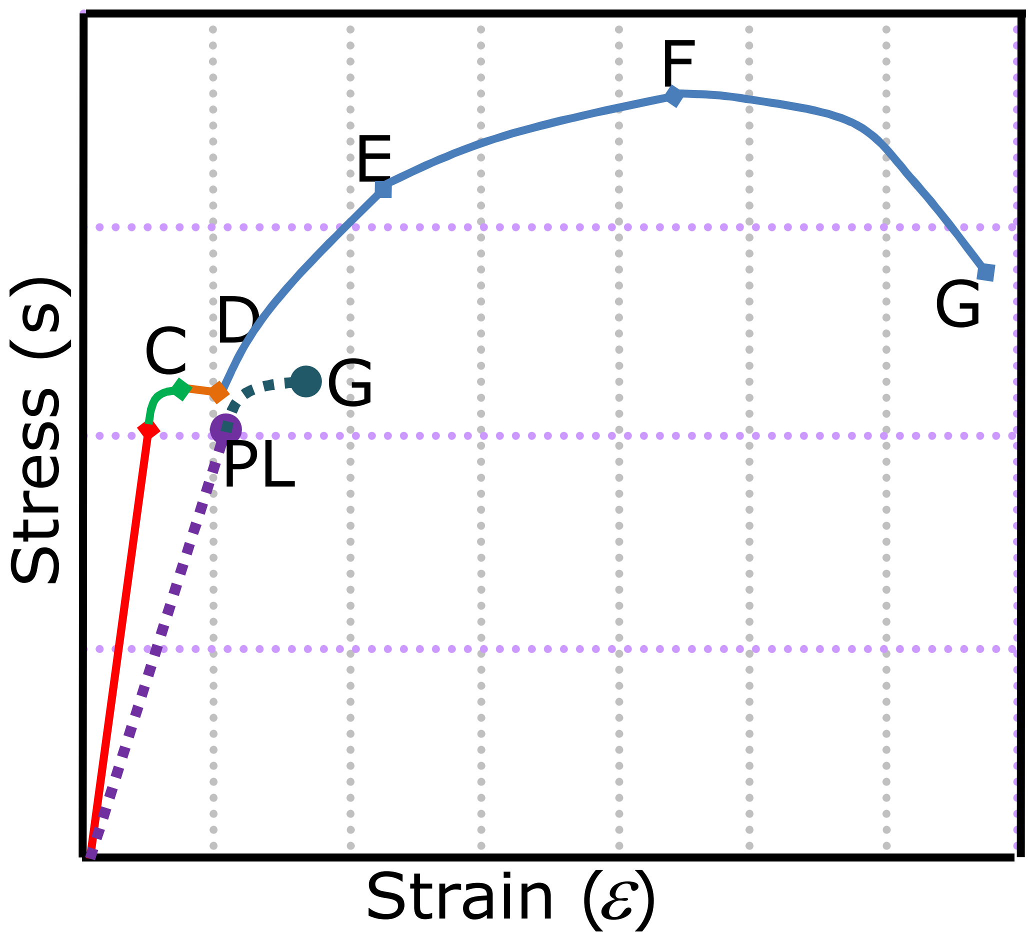
Stress – strain curve



- If this elongating force is removed, specimen regains its original shape – elastic behaviour.

- **C** is called as Yield Point, the stress is Yield Stress. The point **F** is the Ultimate Tensile Stress and **G** is the breakage point.

Stress – strain curve



- Brittle materials also have a Proportional Limit (PL).
- The stress – strain relationship for a brittle material is as shown (Dotted).
- Stresses when exceeded above PL, the brittle material breaks.

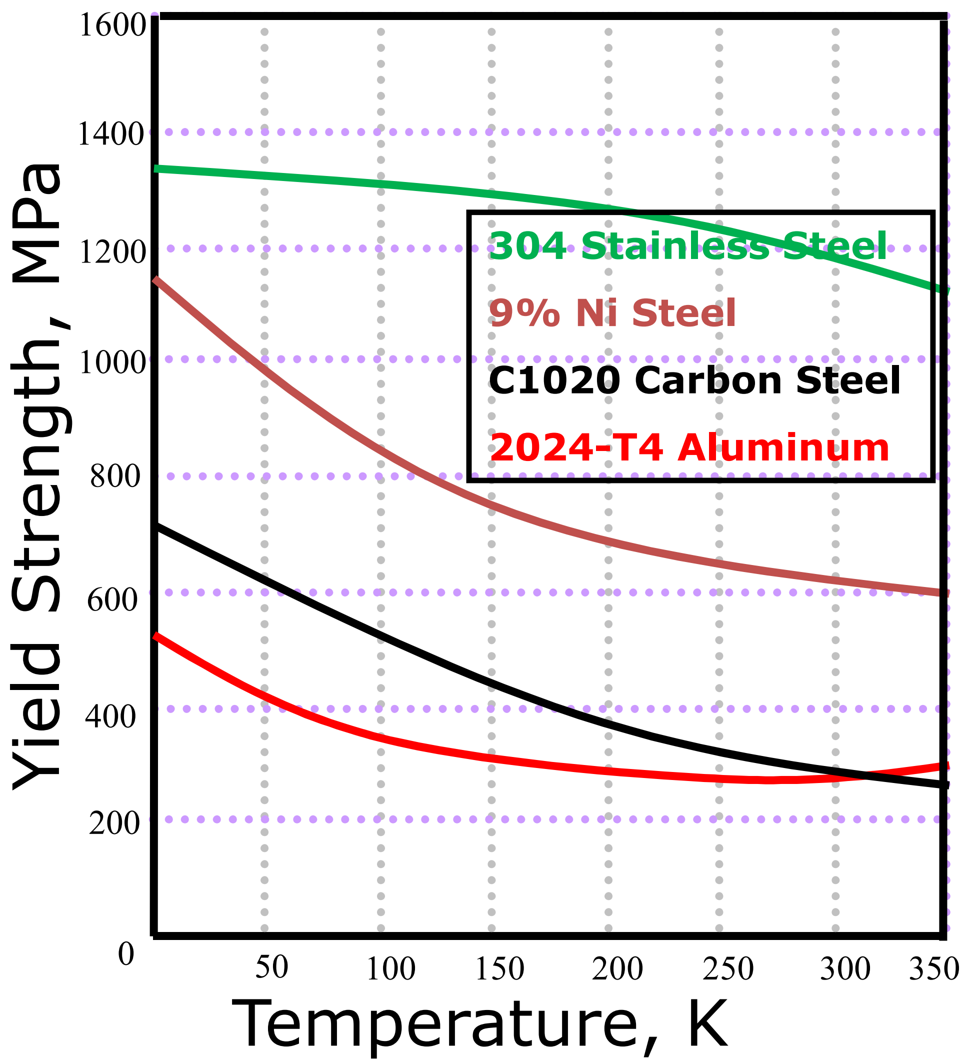
Mechanical Properties

Sr. No.	Property
1	Yield and Ultimate Strengths
2	Fatigue Strength
3	Impact Strength
4	Hardness and Ductility
5	Elastic Moduli

Yield & Ultimate Strengths

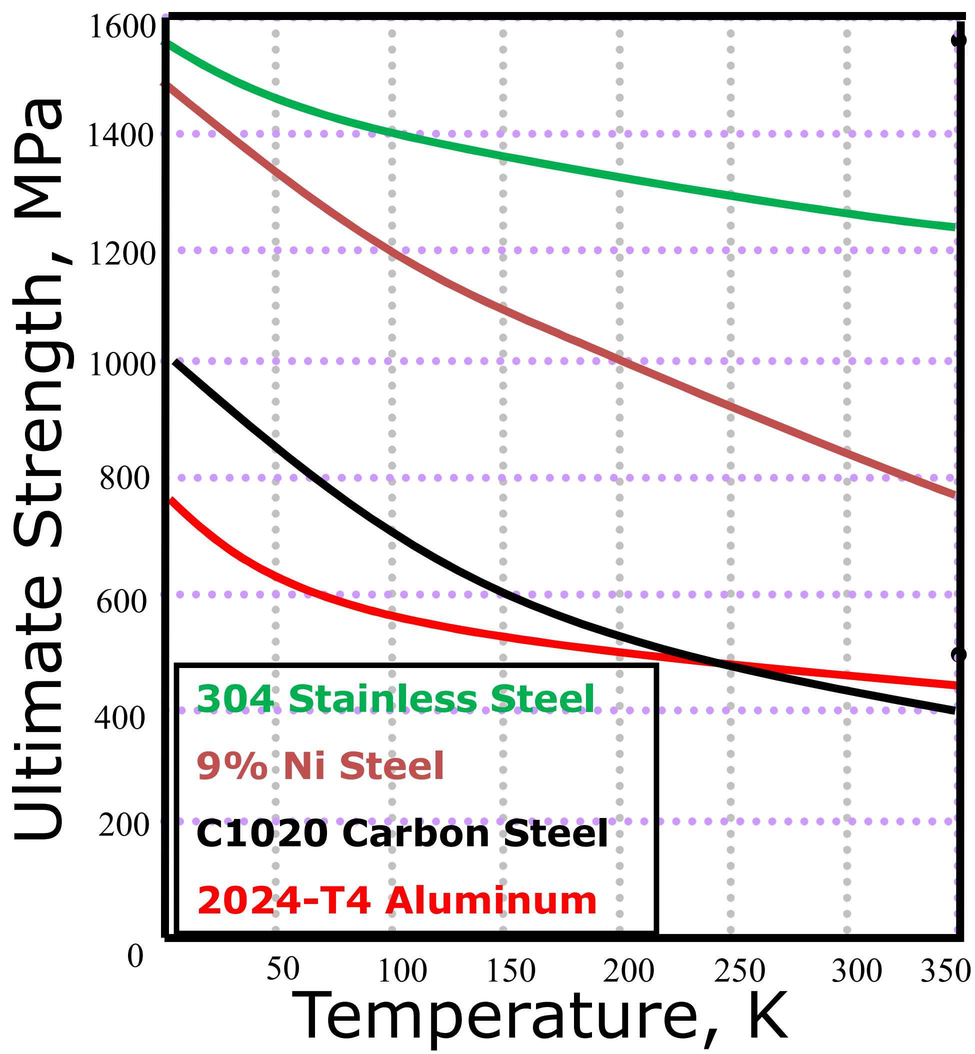
Property	Description
Yield Stress	• It is the stress at which the strain of a material shows a rapid increase with an increase in stress, when subjected to a simple tensile test.
Ultimate Stress	• It is the maximum nominal stress attained by a test specimen during a simple tensile test.

Yield Strength



- The yield strength of various commonly used materials increases with decrease in temperature.
- These materials are normally alloys of iron (steel) and aluminum etc.

Ultimate Strength



Similar to the yield strength, the ultimate strength of the materials also increases with decrease in temperature.

Stainless steel has the high strength and is mostly preferred at cryogenic applications.

Yield & Ultimate Strengths

- The Ultimate and Yield strengths of the material largely depend on the movement of dislocations.

- At lower temperatures, the internal energy of atoms is low.

- As a result, the atoms of the material vibrate less vigorously with less thermal agitation.

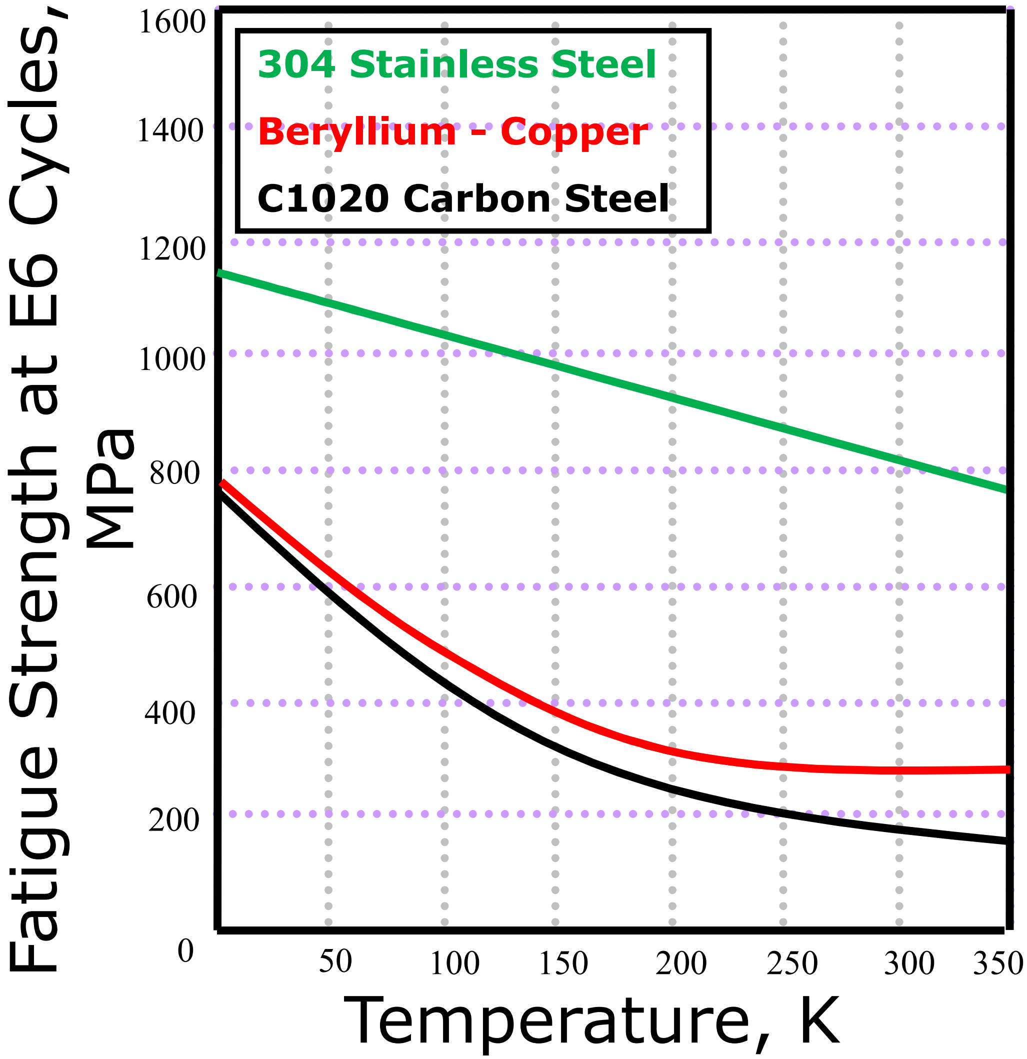
Yield & Ultimate Strengths

- When these agitations are low, the movement of dislocations is hampered.
- It requires a very large stress to tear the dislocations from their equilibrium positions.
- Therefore, materials exhibit high yield and ultimate strengths at low temperatures.

Fatigue Strength

- Materials exhibit fatigue failure when they are subjected to fluctuating loads.
- These failures can happen even if the stress applied is much lower than the ultimate stress values.
- Fatigue strength of a material is the stress at which the specimen fails after a certain number of cycles.

Fatigue Strength



- The fatigue strength increases as the temperature decreases.
- The fatigue strength of stainless steel is higher as shown in figure.

Fatigue Strength

- Any fatigue failure begins with a microcrack initiation.
- At low temperatures, a large stress is required to stretch the crack due to increase in ultimate strength.
- Therefore, like the ultimate strength, the fatigue strength increases as the temperature decreases.

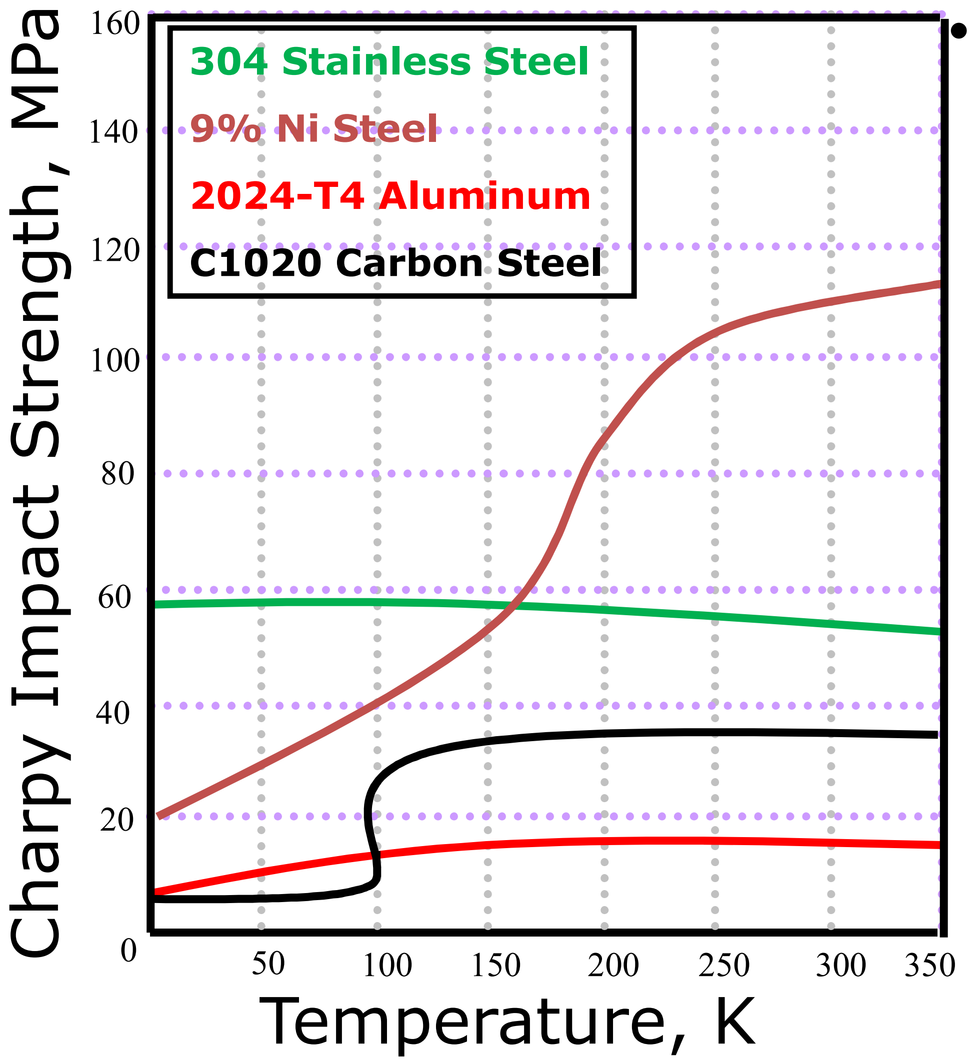
Fatigue Strength

- In order to avoid fatigue failure, when a specimen is subjected to fluctuating loads, the working stress is maintained below a certain value called as Endurance Limit.
- Beryllium – Copper alloy is used in manufacturing of flexure bearings. The working stress is kept below the endurance limit to avoid fatigue failure.

Impact Strength

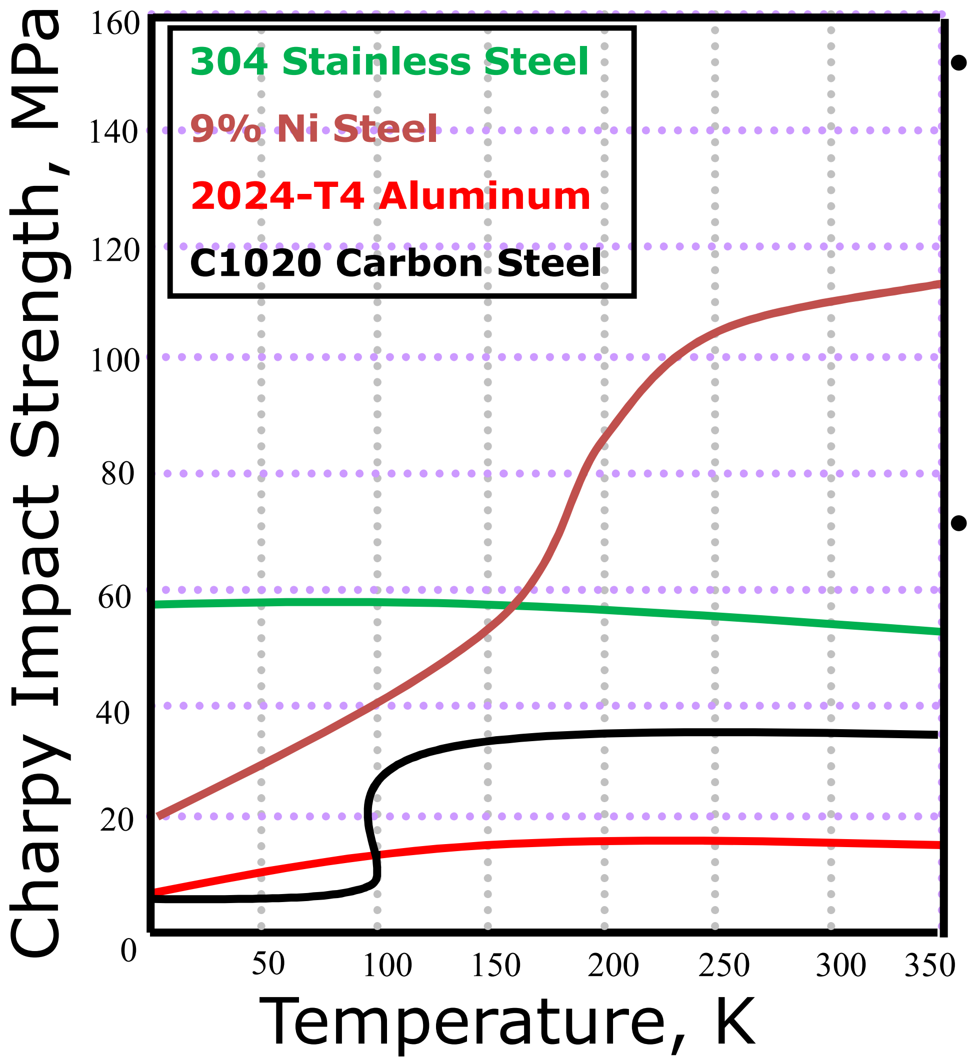
- Charpy and Izod tests are used to measure the resistance of a material to impact loading.
- The energy absorbed when the material is fractured suddenly by a force is the measure of impact strength.
- In both these tests, the difference in the height attained by the hammer pendulum after the impact (loss in potential energy), determines the impact strength of specimen.

Impact Strength



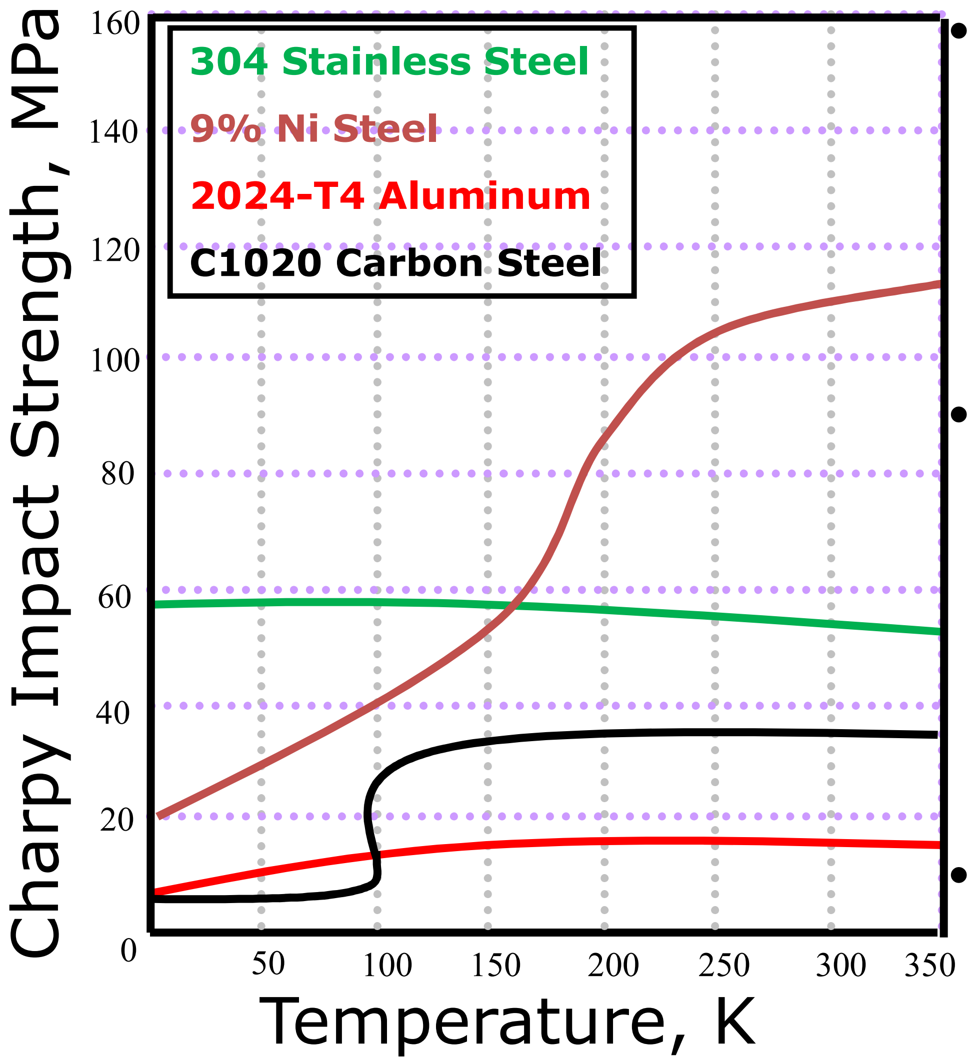
- In general, the impact strength of the materials decreases with decrease in temperature.

Impact Strength



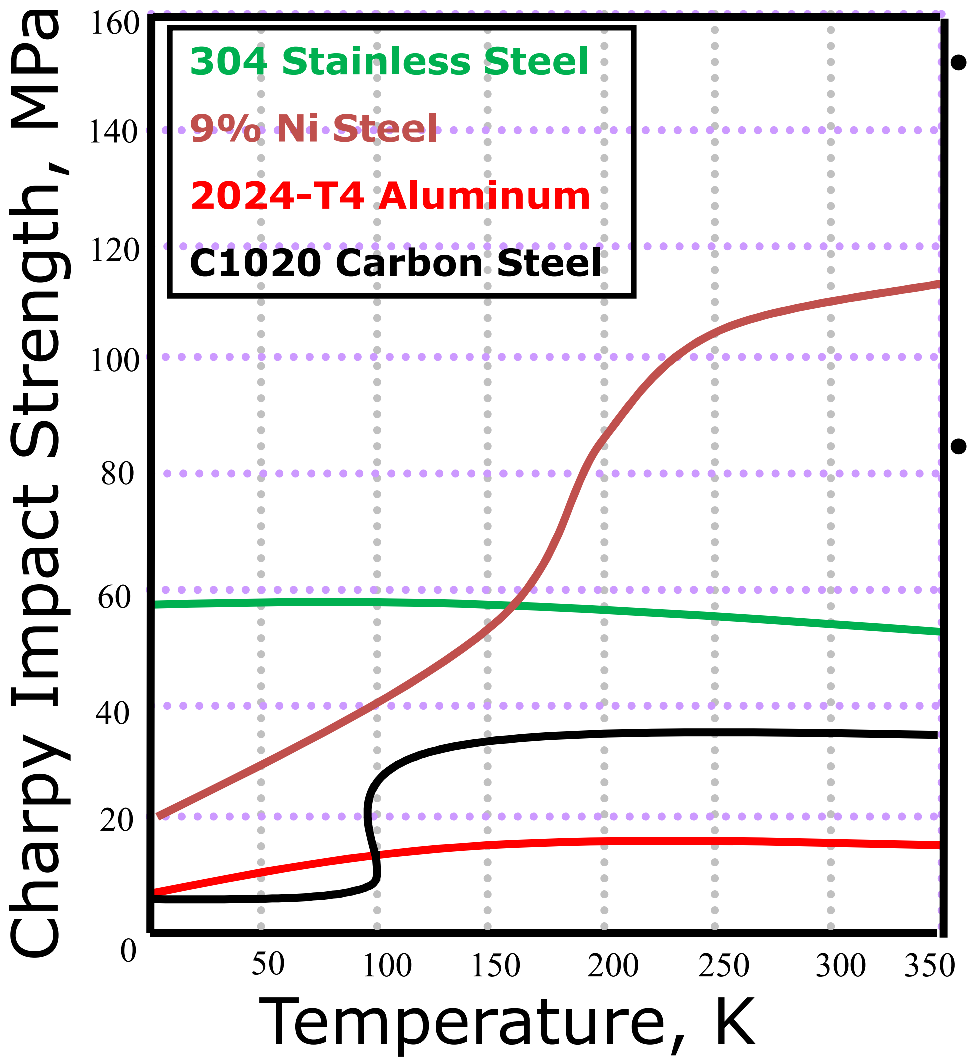
- Few of the materials exhibit Ductile to Brittle Transition (DBT) at low temperatures.
- The temperature at which this occurs is called as Ductile to Brittle Transition Temperature (DBTT).

Impact Strength



- Carbon steels undergo DBT at the temperatures around 80 to 100 K.
- This causes a sudden decrease in the impact strength of the material at that temperature.
- This decrease is as shown by the "**S**" curve in the figure.

Impact Strength



- Hence, these materials cannot be used for cryogenic applications.
- Stainless steel is most preffered material from the impact strength point of view.

Impact Strength

- The impact strength of a material is largely governed by its lattice structure.
- At low temperatures, the materials with Body Centered Cubic (BCC) lattice, break easily.
- This is due to reasons mentioned earlier on the slip planes and movement of dislocations.
- As a result, the materials with BCC lattice are not preferred for low temperature applications.

Impact Strength

- The materials with Face Centered Cubic (FCC) or Hexagonal lattice have more slip planes.
- These slip planes assist in plastic deformation (rather than breaking) and hence increase the impact strength of material even at low temperatures.
- The materials with FCC and HCP lattices are preferred for cryogenic applications.

Ductility

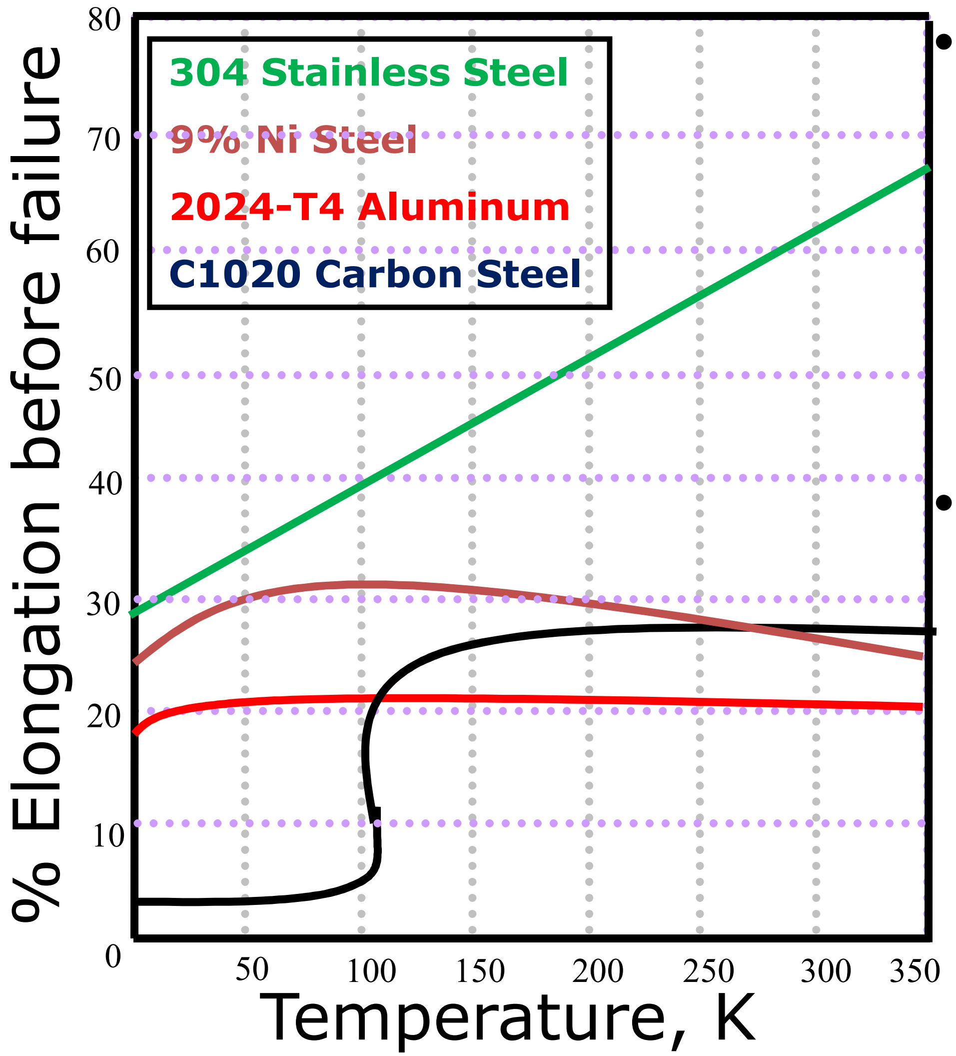
- A material which elongates more than 5% of the original length before failure is called as ductile material.

- When a specimen is subjected to simple tensile test, ductility is given as the measure of

  - Percentage elongation in the length of specimen at the failure (or)

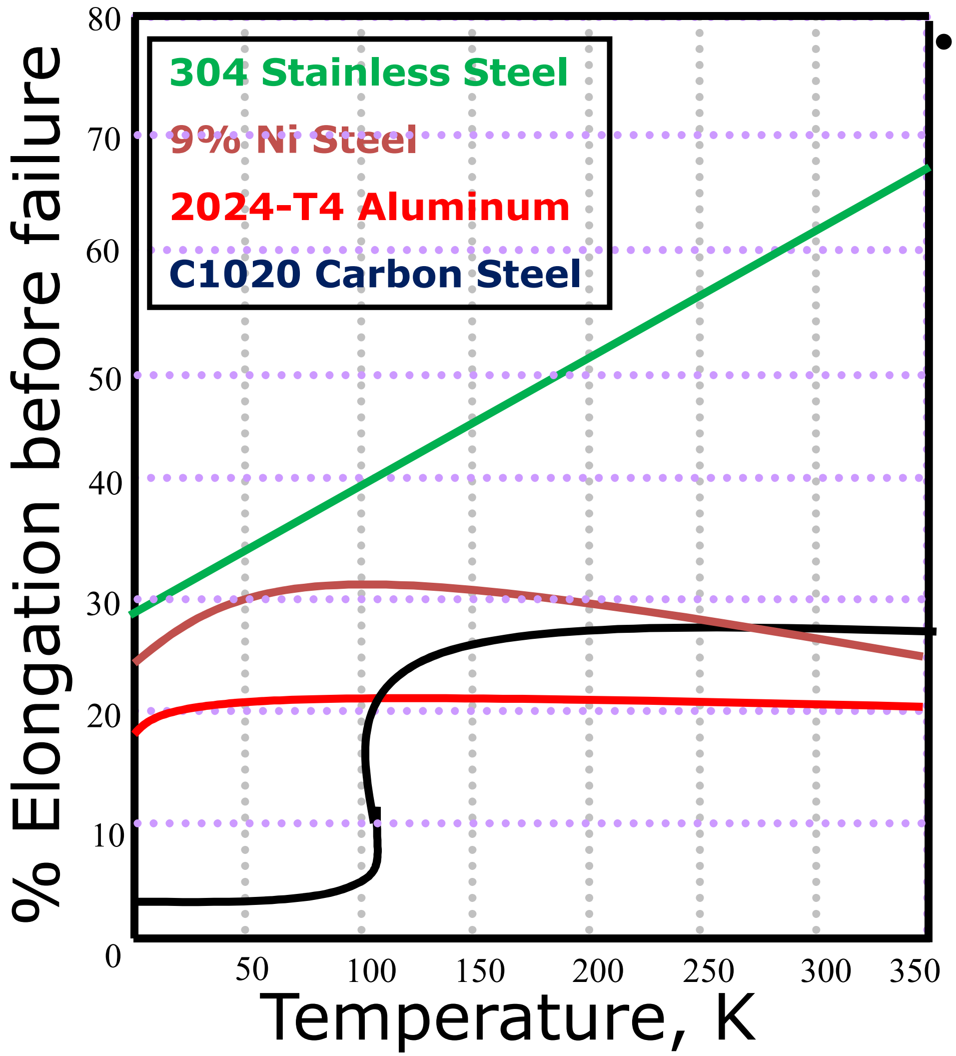
  - Percentage reduction in cross sectional area of the specimen at the failure.

Ductility



- In general, the ductility of the materials decreases with decrease in the temperature.
- The materials which undergo DBT, are not preferred due to the decrease in the ductility.

Ductility



- For stainless steel, the percentage elongation is around 30% at 0 K – meaning fairly ductile for cryogenic applications.

Embrittlement at Low Temp

- Embrittlement of Structural Materials at Low Temperature.

Ductile		Brittle	
FCC	**HCP**	**HCP**	**BCC**
Cu, Ni	Titanium	Zinc	Iron, Carbon
Cu-Ni alloys			Molybdenum
Al & alloys			Niobium
Aust. SS			Most Plastics

Hardness

- Hardness is the measure of depth of the standard indentation made on the surface of the specimen by a standard indenter.

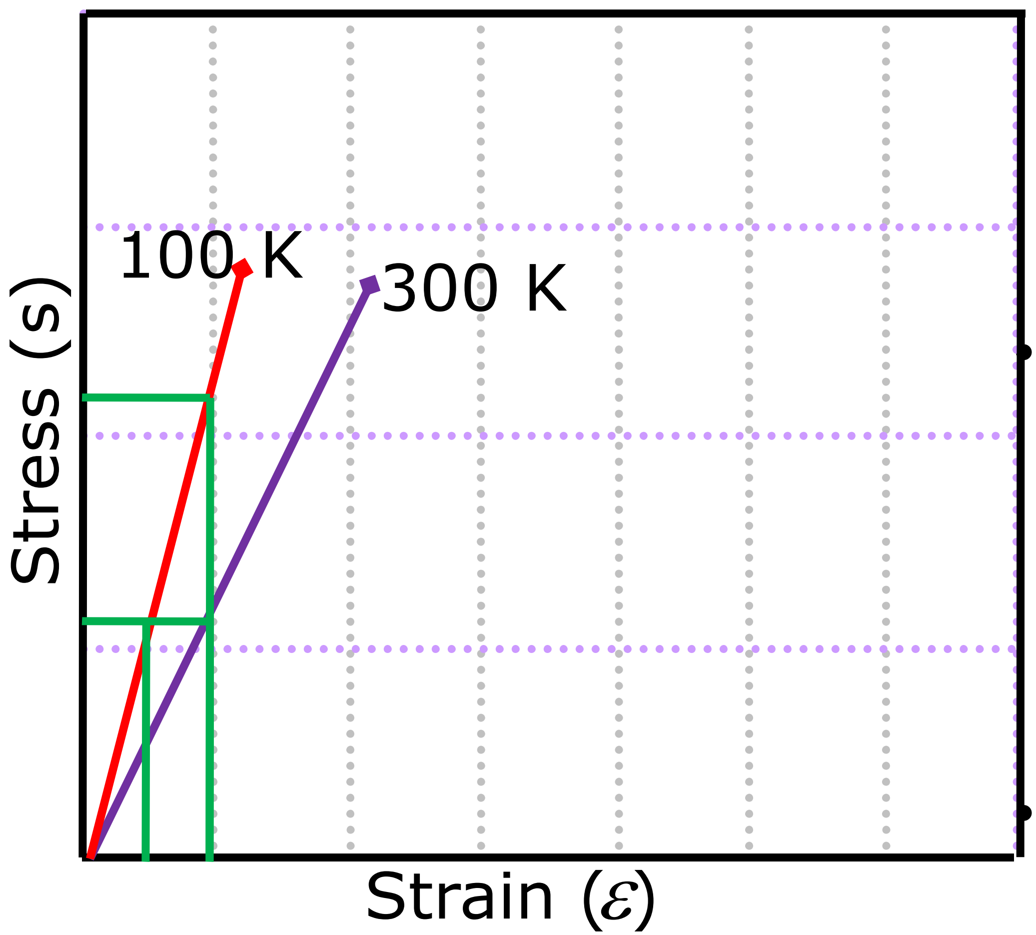
- Common hardness tests inlcude
  - Brinell test
  - Vickers test
  - Rockwell test

- Hardness is directly proportional to the ultimate stress of a material. Hence, it follows the same trend, i.e. increases as the temperature is decreased.

Elastic Moduli

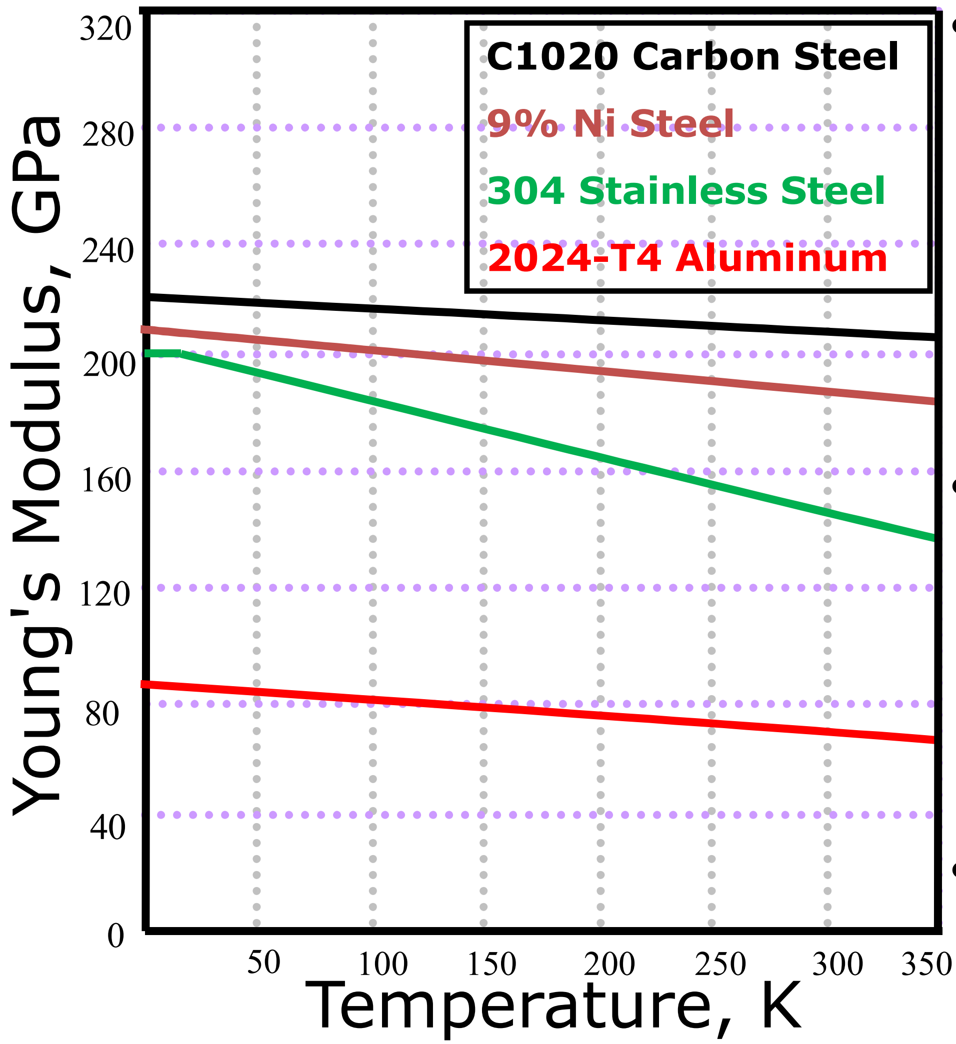
- The three commonly used elastic moduli are
    - Young’s Modulus
    - Shear Modulus
    - Bulk Modulus
- With the decrease in temperature, the disturbing vibrations and thermal agitation of molecules decrease.
- These will increase the inter-atomic forces and thereby, reducing the strain at low temperatures.

Elastic Moduli



- To produce same strain at low temperature, greater stress is required.
- In other words, to produce the same stress at low temperature, less strain is required.
- As a result the Young's modulus increases.

Elastic Moduli

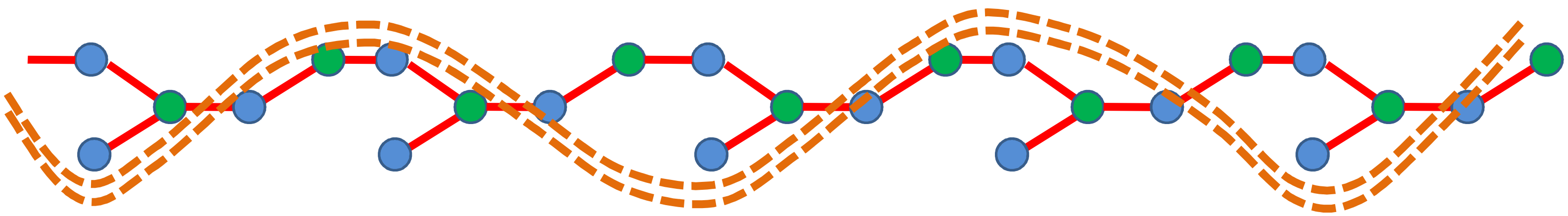


- The Young's modulus of various commonly used materials is as shown in the adjacent figure.
- The elastic moduli increases (slightly) with the decrease in temperature.
- All the three elastic moduli follow the same trend.

Non – Metals (Plastics)

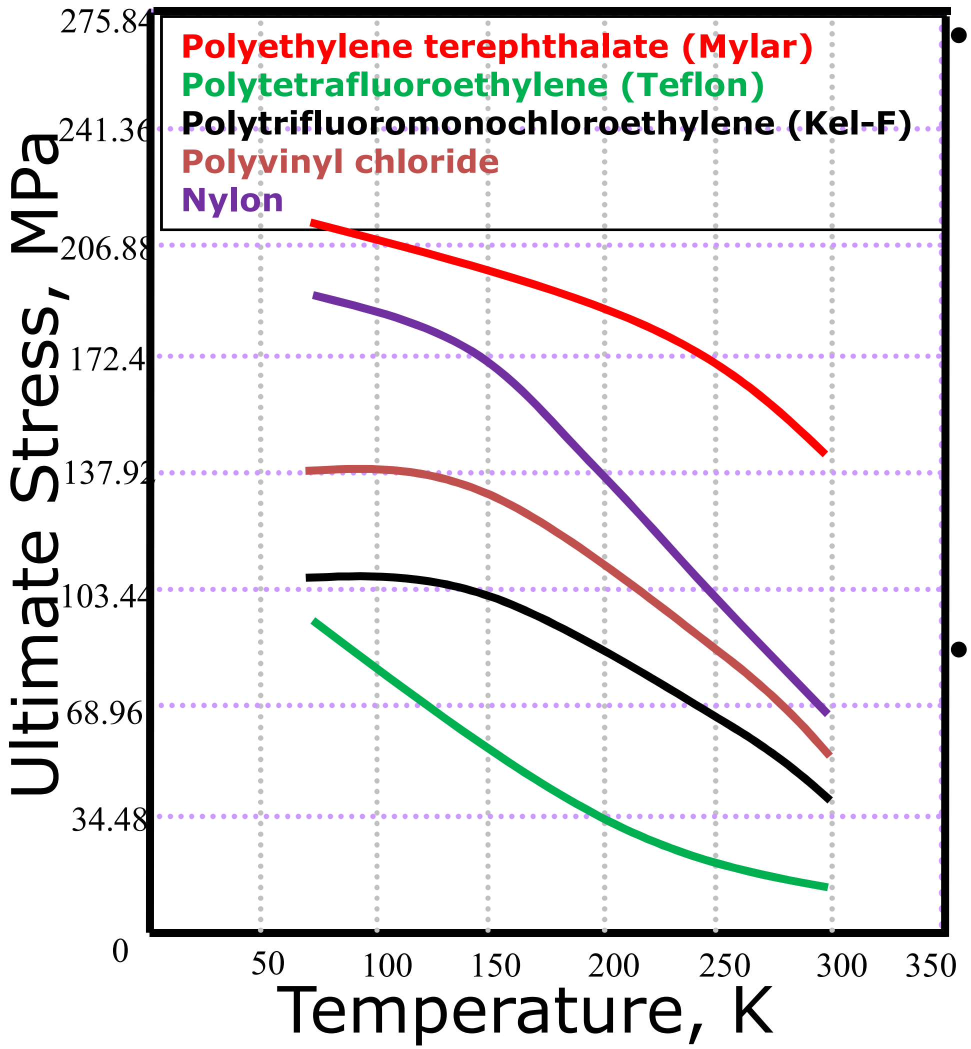
- Plastics or polymers are made of long chains of molecules.

- Each molecule has thousands of atoms held together and arranged in tangled arrays.



- The intermolecular forces that unite the different polymer molecules are van der Waals force.

Tensile Strength (Plastics)



- The strength of various commonly used plastics is as shown. The strength increases with the decrease in the temperature.
- Of all the plastics, PTFE (Teflon) is the only one which can be deformed plastically to a small degree at 4K.

Properties of Plastics

- The effect of stress on plastics or elastomers is very less as compared to metals.
- These solids yield partly by uncoiling the long chain of molecules and sliding over one another.
- This motion is facilitated by the thermal energy possessed by the molecules.
- At low temperatures, material deformation is more difficult due to decrease in thermal energy.

Summary

- Stainless steel is the best material for the cryogenic applications.
- Carbon steel cannot be used at low temperature as it undergoes a Ductile to Brittle Transition (DBT).
- Ultimate and Yield strength, fatigue strength of any material increase at lower temperature while impact strength, ductility decrease at lower temperature.
- PTFE (Teflon) can be deformed plastically at 4 K as compared to other materials.

- A self assessment exercise is given after this slide.
- Kindly asses yourself for this lecture.

Self Assessment

1. Non –metals are classified into _____ and _______.

2. ___________ forces unite the different polymer molecules in plastics.

3. The atoms in a metal are arranged in ______________.

4. The Ultimate Strength of materials ______ with decrease in temperature.

5. _______ metal is mostly preferred in cryogenic applications.

Self Assessment

6. Thermal agitation in molecules is ________ proportional to temperature.

7. _______ failure occurs when materials are subjected to fluctuating loads.

8. _________ is used in manufacturing of flexure bearings.

9. __________ governs the impact strength of a material.

10. _________ property of the material decreases with decrease in temperature.

Self Assessment

11. __________ material cannot be used at low temperatures.

12. _______ crystal structures are most preferred in cryogenic applications.

Answers

1. Glasses, Plastics
2. Van der Waals
3. Symmetrical crystal lattice
4. Increases
5. Stainless steel
6. directly
7. Fatigue
8. Beryllium – Copper alloy
9. Lattice structure

Answers

10. Percentage elongation

11. Carbon steel

12. FCC

Thank You!