Chapter

4

Metals

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4.1 Considerations in Alloy Selection

4.1.1 Introduction

Metals offer a wide variety of physical and mechanical properties for use in the electronics and electrical industries. Because of the demanding requirements on materials in electronic equipment, many trade-offs have to be made in selecting metals. Electrical conductivity must often be reduced to increase strength, while strength is sometimes reduced to obtain a target thermal expansion. These are only two simple trade-offs made in electronic design. Often, the selection involves even more mechanical and/or physical properties along with decisions on economics and manufacturability.

4.1.2 Selection criteria

The process of materials selection involves consideration of the functional requirements with respect to physical and mechanical properties. Feasibility and economics of manufacturing will always be a part of the equation. It does little good to select a material with optimal mechanical properties if the material cannot be fabricated into the desired shape at the required cost. The total design job requires consideration of all the factors of functional material properties and manufacturing processes. Some of the detailed factors to be considered are discussed below.

4.1.3 Composition

Chemical composition is the most commonly specified criterion for metals. This determines the basic mechanical properties and physical characteristics of the metal. Fabrication method and heat treatment will influence these properties, but the chemical composition provides fundamental characteristics. Many metals, such as aluminum and titanium, are used in essentially their pure state, with minor impurity elements. Addition of other elements to a basis metal is common to provide alloys with altered physical or mechanical properties. Alloying elements are controlled to specified limits so that the desired properties may be controlled to given limits. Standardized alloys are available with specified composition limits so that the designer may select the desired properties.

4.1.4 Product forms

The basic chemical composition of a metal or alloy provides the fundamental physical and mechanical properties. However, these properties are often influenced by processing during manufacture to attain the final shape. A material that is bought from a metal producer is generally subjected to a number of operations that will affect its final properties. It is important in many cases that the designer be aware of these variables when selecting a material.

Metals received into an electronics plant for use in manufacturing can be classified as in either cast or wrought forms. These are discussed separately below.

4.1.4.1 Cast metals. Cast metal forms are produced by pouring molten metal into a mold of the desired shape. No metal deformation occurs, and therefore the properties of the metal depend on the casting process (sand, investment, die, and so on), soundness of the casting, chemical composition, and heat treatment. Cast billets for machining into a final shape are sometimes purchased, but in most cases cast parts are molded to their final shape for most dimensions so that a minimum of machining is required to produce a finished part. Casting of complex shapes can often eliminate costly joining, machining, and forming operations, resulting in cost savings in the manufacture of such parts.

A major factor in the properties of cast metals is their soundness, i.e., lack of porosity and nonmetallic defects. Nearly all castings have some defects, such as porosity, gas holes, and shrinkage voids. These defects depend on foundry practice, mold design, pouring practice, and the design of the part. It is important that casting designers consult with foundries during design to reach agreement on defect limits, dimensional tolerances, degree of nondestructive evaluation (NDE), and so forth, because the allowable defects and dimensional tolerances will have an effect on the cost of the part.

The specified mechanical properties for castings are generally based on separately cast test bars. These test-bar values may vary widely from the actual strength of a casting because of existing defects in the casting. Where strength is critical, many foundries will guarantee properties in the actual casting in lieu of separately cast test-bar values. In any case, the properties required of the casting and the means of verification of the properties must be communicated to the foundry.

The cooling rate of metal has a major effect on the properties of the casting. The grain size of the metal decreases as the cooling rate increases, and small grain size generally means increased strength.

Cooling rate is affected by the thickness and mass of the metal shape being cast. Thus, a small, thin-wall casting will be of higher strength than a thicker-wall, massive casting of equal soundness.

The mold material will also affect cooling rate and thus strength. A metal mold (known as a *permanent mold*) will cool a part faster than a sand mold. The mass of the mold, preheating practice, and so forth will also affect the cooling rate.

Castings are widely used in the manufacture of many parts to allow the least amount of machining, joining, and forming. However, they require special care in specifying defect limits and property limits to ensure that required mechanical properties are met.

Not all metals can be readily cast into shapes of any great complexity, although practically all metals are cast into ingots for working into shapes by deformation methods. In the copper, aluminum, and magnesium alloy families, specific alloys have been developed for castings and for wrought alloys. There are exceptions where an alloy may be available as both a casting and as a wrought alloy, but the general separation remains.

In recent years, some special casting processes, such as semisolid metalworking and metal injection molding (MIM), have been used to produce near-net shape castings of low-thermal-expansion materials such as Al/SiC and tungsten-copper. The initial cost of the molds is relatively high for these processes. They are typically feasible where the number of part can justify the high initial cost or the performance achieved by these materials is critical to the application.

4.1.4.2 Wrought metals. The majority of metals and alloys are furnished in a wrought form; that is, the metal has been subjected to some shaping operation by deformation in the solid state. Among these operations are rolling, drawing, extruding, and forging.

Such operations will have major effects on the final properties of the material. These operations affect grain size, crystallographic orientation, homogeneity, soundness, size and shape of inclusions, size and shape of metallurgical phases, and so on. These factors affect strength and ductility, formability, directional physical and mechanical properties, as well as reaction to subsequent heat treatment.

The temperature at which the metal is deformed or worked is important in its effect on properties. Hot-working is defined as deformation done at temperatures above the recrystallization temperature of the metal. The recrystallization temperature is that temperature above which a metal will form new, strain-free grains as rapidly as the old grains are strained by the working process. At high temperatures, the metal is not hardened by the working process; thus, large amounts of deformation may be carried out without fracturing the metal.

Cold-working takes place below the recrystallization temperature and thus results in strain hardening of the material, because new grains cannot be formed to relieve the strain set up by deformation.

Wrought metals are formed to shape by either hot-working alone or by combinations of hot-working and cold-working. Simplified descriptions of some of the wrought product procedures follow.

4.1.4.3 Extrusion. This process generally uses a billet as raw material. In most cases, the billet is a casting. The billet is heated above the recrystallization temperature and then forced through a die of suitable shape to form the finished shape. As can be seen by the description, this is a hot-working process in essentially one direction. No appreciable work hardening occurs in this process. In some metals, the tensile strength is considerably higher than the compressive strength in the longitudinal direction. Often, it is the lowest-cost method to produce shapes with complex cross sections.

4.1.4.4 Forging. This is generally a hot-working process that starts with a cast billet that is shaped by hammering or pressing to form a shape. To obtain optimal properties, it is important that the cast structure be completely worked to form a grain structure and to close up shrinkage voids in the cast billet. The mechanical properties of forgings will depend to some extent on the flow direction of the metal during forging. For highest strength, forging suppliers should be consulted during design to ensure that the correct flow pattern can be attained.

4.1.4.5 Rolling. Sheet, plate, strip, and many bars and shapes are formed by rolling. This process accounts for the longest tonnage of metal produced.

Rolled parts typically begin with a large cast billet, which is heated well above its recrystallization temperature and reduced to a slab or billet by rolling. This slab or billet is then hot-worked to some thin long shape such as sheet. Hot-rolling helps to break up the large grains common to cast structures found in the ingot, replacing it with finer, uniform, recrystallized grains. The rolling also tends to close in voids, resulting in a more dense, defect-free metal. This is an essential step in getting a high-quality product.

Hot-rolled products tend to have relatively rough surfaces with some rolled-in scale. This, of course, is not desirable for most electronic purposes. The mechanical properties of hot-rolled properties are generally close to the annealed (or weakest) properties for that particular composition.

Some rolled products used in the electronics industry are given final shaping to finished dimension by cold-rolling after initial hot-rolling. This rolling results in better surface finishes, closer dimensional tolerances, and (under proper control) can result in higher strength as a result of cold-working. In some cases, this may result in a cost savings if the closer tolerance results in fewer machined surfaces. Many metals achieve their high-strength properties via strain hardening by cold-working. Many aluminum, copper, magnesium, and nickel alloys, and all pure metals, cannot be strengthened beyond their annealed strength by any method other than strain hardening.

In metals and alloys that are hardened by strain hardening, the thickness of the section being used significantly affects the degree of strengthening. Thin sheet, which can be thoroughly deformed through the entire thickness, will have higher strength than thicker material, which does not get worked thoroughly. The designer should be careful not to assume that strengths shown for one thickness apply to all thicknesses.

Strain hardening can give desirable increases in strength, but it also reduces ductility and formability. Reduction in electric and thermal conductivity can result from strain hardening. Stress corrosion can be another detrimental effect of strain-hardened materials.

4.1.5 Strengthening mechanisms

To adequately specify metals and their processing, the designer should have a knowledge of the strengthening mechanisms and the interactions of these mechanisms with the manufacturing process. The major hardening mechanisms are discussed below, along with some of the limitations and advantages offered by these methods.

4.1.5.1 Strain hardening. As discussed above, cold-working results in distortion of the crystal structure of metals, thus causing an increase in strength and hardness. Practically all metals strain harden to some extent, and it is the only way to strengthen some metals.

When strain-hardened metals are used in service, care must be taken that manufacturing processes do not exceed the recrystallization temperature of the metal. Such temperatures will result in loss of the strain hardening, and the metal will revert back to the annealed state. Such processes as welding and brazing are prime examples of heat sources that will reduce work-hardened materials back to their annealed state.

4.1.5.2 Precipitation hardening (age hardening). Many alloy compositions are such that the solid solubility of one metal into the other increases with temperature. By heating the alloy to a temperature at which the solubility is high and then quenching quickly to room temperature, the solute is retained in solution. Essentially, the alloying elements dissolve into the base metal. This process is known as *solution treating.* Subsequent aging at a suitable temperature precipitates out the solute uniformly throughout the crystallographic structure, causing lattice distortions that result in an increase in mechanical properties. Some alloys are aged to some degree at room temperature. Care must be taken not to exceed the specified time or temperature of the precipitation-hardening treatment. An overaged condition results wherein the mechanical properties are greatly reduced.

Materials of this type offer the advantage of allowing forming or other working in the annealed or soft condition, with subsequent heat treatment to produce higher strength. Also, parts may be welded, brazed, or otherwise heated during fabrication and then brought to high strength after these operations by solution treating and aging.

The sequence of solution treating and aging can be varied somewhat, depending on the circumstances. As mentioned above, both solution treating and aging may be carried out on the final assembly. One disadvantage of this procedure is that the fast cooling required for solution treatment may result in distortion. However, to get full strength from an assembly that has been heated above the aging temperature, this sequence is necessary.

Forming of metal in the solution-treated condition is done in many cases. The solution-treated condition is usually relatively ductile, thus permitting reasonable formability. After forming, a relatively low-temperature aging will result in full strength and hardness. Another variation of this procedure is to solution treat the raw stock just before forming. This takes advantage of the fact that solution-treated material is softest immediately after solution treatment. Examples of precipitation hardenable alloys include 17-4PH steel and 6061 aluminum.

4.1.5.3 Phase-transformation hardening. Some alloys, notably certain titanium alloys and many steels, are hardenable by manipulation of phase transformations. This mechanism takes advantage of the fact that a normally two-phase alloy can be converted to a one-phase alloy by heating to elevated temperature. Quenching from this temperature results in this single phase being retained at room temperature. Subsequent aging at moderately elevated temperature will cause the alloy to revert to the two-phase structure, but with much finer particles of each phase than would occur under equilibrium conditions. This fine structure results in increased strength and hardness.

Many metals are supplied with combined strengthening mechanisms. The most common instance is that of a material that is solution treated and then cold-worked by rolling or stretching, after which it is aged. This combination results in higher strength than could be attained by heat treatment or cold-working alone.

It is obvious that selection of a metal or alloy must take into consideration not only the final strength desired but also the feasibility of maintaining or attaining that property in fabrication.

4.1.6 Mechanical properties

After chemical composition, the most commonly specified properties are the tensile properties. Usually, these consist of ultimate strength, yield strength, and percentage elongation as determined on a standard tensile test bar (per ASTM E8, for example). These properties are often all that need to be known to make a material selection for mechanical design. These values, however, represent data taken on machined test bars at room temperature under one short-time loading. A number of factors that will reduce the design allowable stresses to well below the published tensile values are discussed below.

4.1.6.1 Repeated loads (fatigue). When loads are repeated, the allowable stress is reduced well below the tensile strength of the material. In other words, the metal will fail at stress levels well below the yield or ultimate tensile strength. With most nonferrous materials subjected to 10 million cycles of stress, the breaking stress can be one-third of the tensile strength. In considering fatigue data, attention should be paid to the type of specimen, the type of loading, and the condition of the test specimen with regard to notches. The presence of notches can further reduce fatigue stress to as low as one-fifth of the tensile strength. Improvement in fatigue has been brought about by improving surface finish and by various other methods.

The subject of fatigue is very complex and subject to some controversy. In designing for repeated loads, special attention should be given to the available data. Specific tests under service conditions are also recommended.

4.1.6.2 Sustained loads. Failure under long-time sustained loads may occur as a result of creep or fracture at stresses below the yield strength, as determined by the standard tensile test. Although this type of failure is thought of as occurring at relatively high temperatures, such phenomena do occur at room temperature.

4.1.6.3 Temperature effects. The strength of metals decreases as temperature increases. Ductility generally increases until temperatures near the melting point are reached. The reverse occurs on lowering temperature; that is, strength increases and ductility decreases. The decreasing ductility with decreasing temperature is not particularly severe with nonferrous alloys. No drastic embrittlement occurs, even at cryogenic temperatures.

It can be seen that the room-temperature tensile test values can be useful in the selection of materials, but the service conditions and type of loading can be important factors in selecting a safe design stress.

4.1.7 Physical properties

Physical properties are a result of chemical composition, atomic arrangement, and temperature. In considering data on physical properties, the above factors should be considered. Practical situations in which significant changes in physical properties occur are briefly discussed below.

4.1.7.1 Cold-working. Slight decreases in electrical conductivity are experienced with cold-working on strain hardening.

4.1.7.2 Heat treatment.

Heat treatment has various effects on the structure and distribution of alloying elements and phases and thus will often have major effects on physical properties, including electrical conductivity, thermal conductivity, density, thermal expansion, and sometimes elastic modulus. Many of these changes are insignificant for engineering purposes, but the electrical conductivity differences can be quite dramatic.

Precipitation hardenable alloys are especially prone to change in electrical conductivity with a change in heat-treat condition. The solution-treated condition usually has the lowest conductivity, because the alloying elements are in solution, a condition that gives low conductivity. Annealing results in conglomeration of the alloying elements, thus giving the effect of a mixture wherein the two phases may average out. Aging of solution-treated materials will usually result in some increase in electrical conductivity, but not to the extent that results from annealing.

Because of the crystal structure, some metals change in density when heat treated. Beryllium-copper is one such material. Beryllium-copper (UNS C17200, for example) is also an example of a material that undergoes a change in elastic modulus as a result of heat treatment.

4.1.7.3 Temperature.

Physical properties change with temperature. Most of these changes are gradual. If the temperature changes result in a phase change, drastic changes in physical properties can occur. In magnetic materials, increasing temperature beyond the Curie temperature results in material becoming nonmagnetic.

It can be seen that, in using physical property data, attention should be paid to the details of service temperature and material condition.

4.1.8 Manufacturing considerations

Selection of the material must always take into consideration the manufacturing processes to be used in fabricating the part. Material must be selected that can be processed to the final configuration economically.

Metallurgical properties of the materials selected will greatly influence the machinability, formability, and joining ability. Many times, compromises can be made to enhance manufacturing of the item. Knowledge of available fabrication equipment is also useful.

Some of the basic material characteristics that can be used to select materials for fabrication are discussed below.

4.1.8.1 Formability.

The tensile test values for a material can be used as a reasonable guide for the selection of a formable material. The percentage elongation is a good indication of how much a material may be deformed. Also, a large difference between the ultimate tensile strength and the yield strength indicates good formability. Minimum recommended bend radii are also published for most materials and are sometimes included in specifications.

For drastic forming operations such as deep drawing, more sophisticated specifications of material properties are required. Grain size control is one of these. An optimal grain size along with a minimum elongation exists for most materials.

4.1.8.2 Machinability. Most metal alloys can be machined without great difficulty. Many alloys are made with specific chemical additions that improve machinability. These additions usually have the advantage that small chips are formed during machining. Many of these alloys have the disadvantage of being less formable, more brittle, and less weldable because of these additions. Care should be taken that the free-machining additions do not interfere with other fabrication techniques or sacrifice mechanical properties.

4.1.8.3 Joining. Alloy selection for joining is critical in designing a welded part. Often, the alloy selection determines the joining method, and vice versa. Bolting, riveting, and other mechanical methods offer no real problem for most metals, but the metallurgical processes of welding, brazing, and soldering require considerable planning.

4.1.8.4 Weldability. The ratings on weldability are qualitative and are generally based on ability to be welded with conventional techniques. A metal or alloy may get a poor weldability rating for a number of reasons, including (1) tendency to crack during welding, (2) poor corrosion resistance of the weld, and (3) brittleness of the weld. To some extent, weldability becomes a function of the process that is used for welding. Much of the success in welding reactive metals such as aluminum, magnesium, and titanium is a result of the use of the inert-gas-shielded-arc methods of welding, wherein the molten metal is shielded from the air atmosphere by an inert gas. The development of the electron beam, with its narrow, deep-penetration weld, has resulted in successful welding of alloys and combinations of alloys that were formerly considered nonweldable. In addition, some solid state processes, such as roll bonding, explosive bonding, and friction welding, can produce an excellent metallurgical bond between dissimilar metals.

4.1.8.5 Brazing. Selection of an alloy to be brazed requires consideration of the melting point of the alloy to be brazed as compared to melting point of the brazing alloy. The relationship of the brazing temperature to the heat treating to be performed on the part should also be considered. If it is desired to have the final properties of the part in the heat-treated condition, the brazing alloy must have a melting point above the heat-treating temperature. The method to be used for brazing is important. Torch brazing locally heats the joint and may result in distortion. Furnace brazing requires heating of the whole part, resulting in less distortion but requiring fixturing in most cases. Induction brazing offers fast, localized heating. Dip brazing requires immersing the complete area to be brazed in a molten flux bath.

4.1.8.6 Soldering. Soldering is a low-temperature process that can be used on a wide variety of metals. Some nonferrous metals, such as aluminum and magnesium, are soldered with difficulty unless the surface is plated with a metal that is more easily soldered (tin, for example). Normal solders generally form galvanic cells with these alloys, and joints with poor corrosion resistance in the presence of moisture will result. These alloys may be plated with solderable coatings and then soldered much as other metals. Soldering is covered in detail in Chapter 5.

4.2 Comparative Data on Metals

It is obvious that, with the thousands of metal and alloy compositions available, and with the varying degrees of strain hardening, heat-treating conditions, and varying service temperatures, it is impossible to list all data for all conditions. A comparison of the range of properties available in an alloy group can usually narrow the selection greatly. Some general comparisons of a wide range of metals follow.

4.2.1 Yield strength comparisons

The yield strength of a metal is generally defined as the maximum stress to which a part is subjected in service. Figure 4.1 gives a comparison of the yield strengths of a number of alloys. It can readily be seen that there is a wide overlap of yield strength among the commonly used alloys. At stress levels below 40,000 psi, most alloy families have alloys that are adequate, and selection would be made on the basis of some other property or on cost factors.

4.2.2 Modulus of elasticity (Young's modulus) and stiffness

Figure 4.2 compares the elastic moduli of a number of alloys. Since this property indicates stiffness of a part, it plays an important design role. Note that there is little significant variation in elastic modulus for any one alloy family, even though yield strengths may vary as much as 20× in some alloy families.

Specific stiffness is calculated by dividing the elastic modulus by the density. In Fig. 4.3, various alloys are compared. Note that the commonly used structural metals such as aluminum, magnesium, and titanium are about the same, whereas nickel and copper alloys have somewhat lower values. The only standout material in this property is beryllium, with a value of 6 to 12 times that of common structural materials.

4.2.3 Strength-to-density ratios

In Fig. 4.4, the strength-to-weight ratios of a number of materials are compared. This figure shows that, when compared on a weight basis, some of the

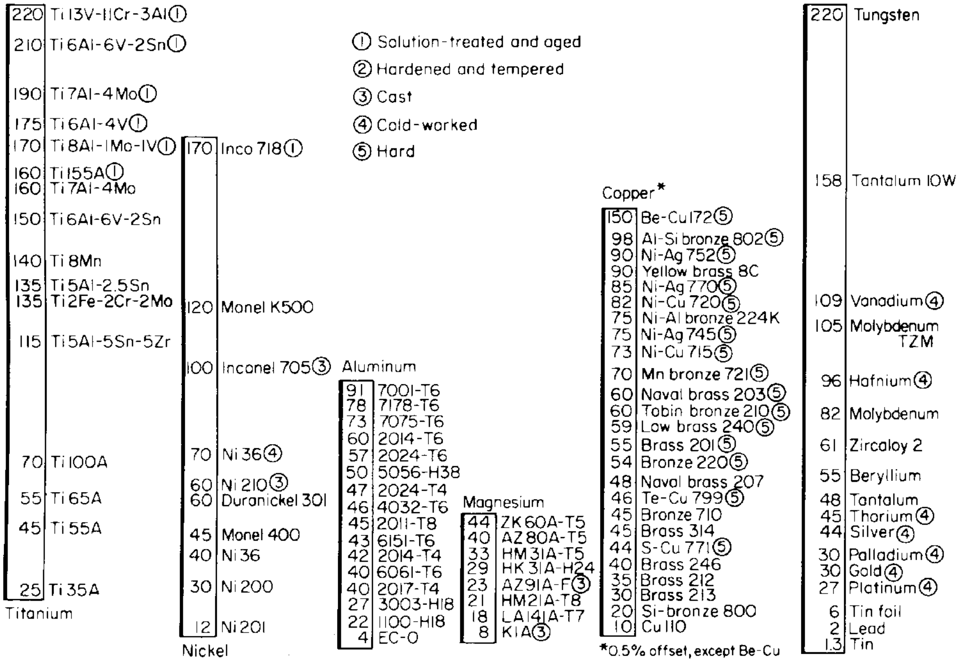

Figure 4.1 Tensile yield strengths of some nonferrous metals at room temperature (typical values × 1000).

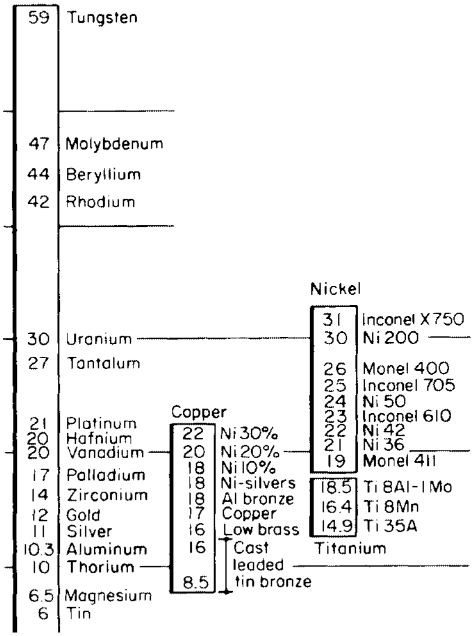

Figure 4.2 Modulus of elasticity of some nonferrous metals at room temperature (typical values × 1000).

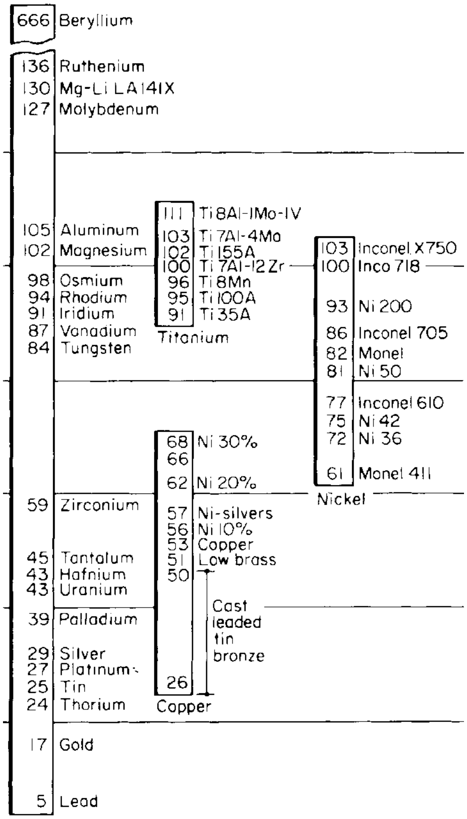

Figure 4.3 Specific stiffness of some metals at room temperature (typical values, modulus of elasticity × 10^6/density).

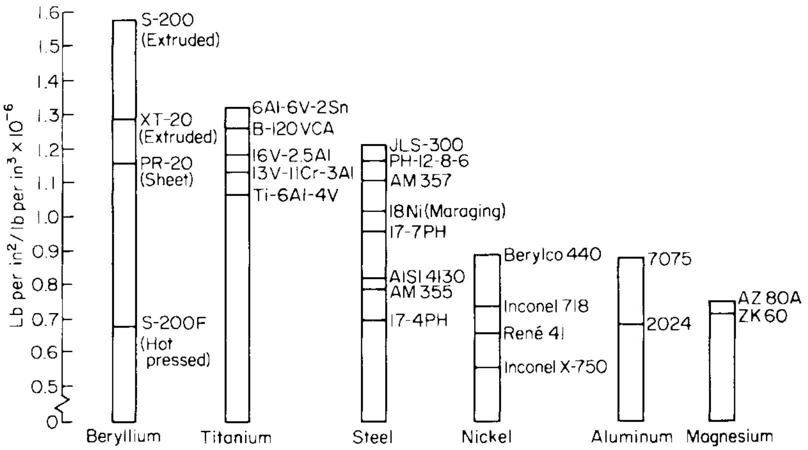

Figure 4.4 Ultimate tensile strength-to-density ratios of various structural materials at room temperature.

weaker, low-density materials are superior to the high-strength, high-density materials. Note that room-temperature comparisons do not necessarily hold at elevated temperatures.

4.2.4 Thermal conductivity

In Fig. 4.5, thermal conductivities are compared. It can be seen that the pure metals—silver, copper, gold, and aluminum—have the highest thermal conductivities. Alloying in general lowers the conductivity, sometimes drastically.

4.2.5 Electrical resistivity

Figure 4.6 graphs the comparative electrical resistivity of certain metals. Again, it should be pointed out that alloying will drastically affect electrical resistivity.

4.2.6 Heat absorption

Figure 4.7 gives a comparison of the ability of metals to absorb heat. These values are for pure metals (with the exception of steel), and alloying can result in drastic changes. In addition, Table 4.1 lists the thermal properties of a

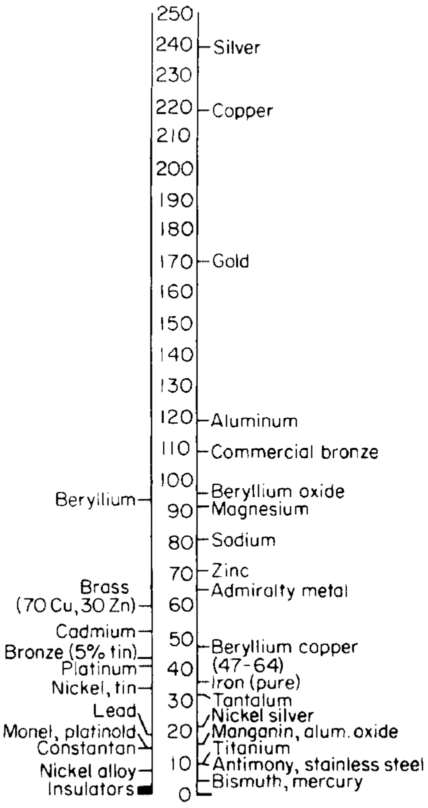

Figure 4.5 Thermal conductivity at 100°C for some materials.

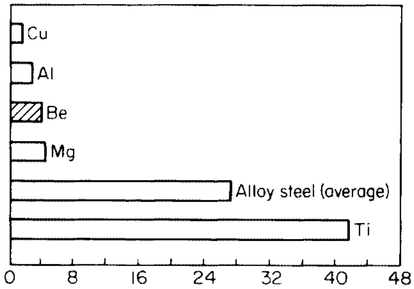

Figure 4.6 Comparison of the electrical conductivities of several pure metals.

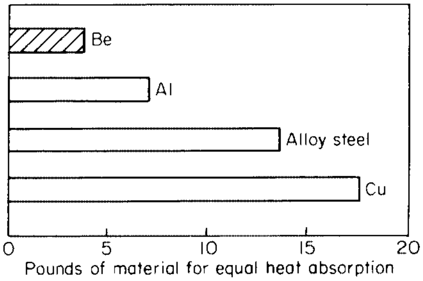

Figure 4.7 Comparison of the heat absorption of several pure metals.

TABLE 4.1 Thermal Properties of Several Pure Metals

Property	Be	Mg	Al	Ti	Fe	Cu
Melting temperature						
°C	1277	650	660	1668	1536	1083
°F	2332	1202	1220	3035	2797	1981
Boiling temperature						
°C	2770	1107	2450	3260	3000	2595
°F	5020	2025	4442	5900	5430	4703
Thermal conductivity, cal/(sec)(cm^2)(°C/cm)	0.35	0.367	0.53	0.41	0.18	0.94
Linear thermal expansion		27.1	23.6	8.41	11.7	16.5
µin/(in)(°C)	11.6	15.05	13.1	4.67	6.5	9.2
µin/(in)(°F)	6.4					
Specific heat, cal/(g)(°C)	0.45	0.25	0.215	0.124	0.11	0.092
Heat of fusion, cal/g	260	88	94.5	104*	65	50.6

*Estimated.

number of pure metals. The above data were presented to give a first cut at comparisons among metals, in an effort to give the designer an idea of the range of properties available.[8]

4.2.7 Ferrous metals (steels)

4.2.7.1 General properties. An alloy containing 50 percent or more of iron is considered to be a ferrous alloy. This section, however, also includes information on alloys that contain below 50 percent iron, because their specific desired properties are similar to those of the ferrous alloys. Ferrous alloys are divided into several categories such as typical compositions, specific properties, and standard trade designations. All three classes are employed; the class designations selected are those most commonly used in the industry. Many types of properties are sought from these alloys; i.e., magnetic properties, thermal expansion, electrical resistivity, thermal conductivity, corrosion resistance, and physical properties. Alloys discussed herein are classified by the following methods:

1. Typical composition when produced by two or more sources and each having a different brand name
2. Industry-designated brand names utilized by all sources such as the American Iron and Steel Institute (AISI)
3. Brand name if only available from one source

Various properties for these alloys are explained in terms commonly used in the industry. If the desired properties are not expressed in the units desired, conversion factors, in all probability, can be found. Properties not reviewed here may be available from producers of the alloys.[9]

4.2.7.2 Alloy groups. The high-strength, low-alloy, quenched and tempered, and some of the ultrahigh-strength steels were developed in recent years. They meet industry needs for weight reduction, higher performance, and, in many cases, lower costs. The disadvantage from the designer's standpoint is that it is becoming difficult to categorize steels in an orderly fashion to aid selection. The common denominator for the steel systems is use. They are the types of steels that would be used for structural components. Figure 4.8 outlines the categories. Even with the abundance of special-purpose steels, the workhorses are and for some time will continue to be the wrought ASTM, AISI-SAE carbon and alloy steels. Fortunately, these steels have an understandable and orderly designation system.

4.2.8 Composition-wrought ferrous alloys

4.2.8.1 Carbon and alloy steels. The most important identification system for carbon and alloy steels in the U.S. is the system adopted by the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). This system usually employs only four digits. The first digit indicates the grouping by major alloying elements. For example, a first digit of 1 indicates that carbon is the major alloying element. The second digit, in some instances, suggests the relative percentage of a primary alloying element in a given series. The 2xxx series of steels has nickel as the primary alloying element. A 23xx steel has approximately 3 percent nickel; a 25xx steel has approximately 5 percent nickel. The last two digits (sometimes the last 3) indicate median carbon content in hundredths of a percent. A 1040 steel will have a normal carbon concentration of 0.40 percent. The classes of steels in this system are shown in Table 4.2. In addition to the four digits, various letter, prefixes, and suffixes provide additional information on particular steels.

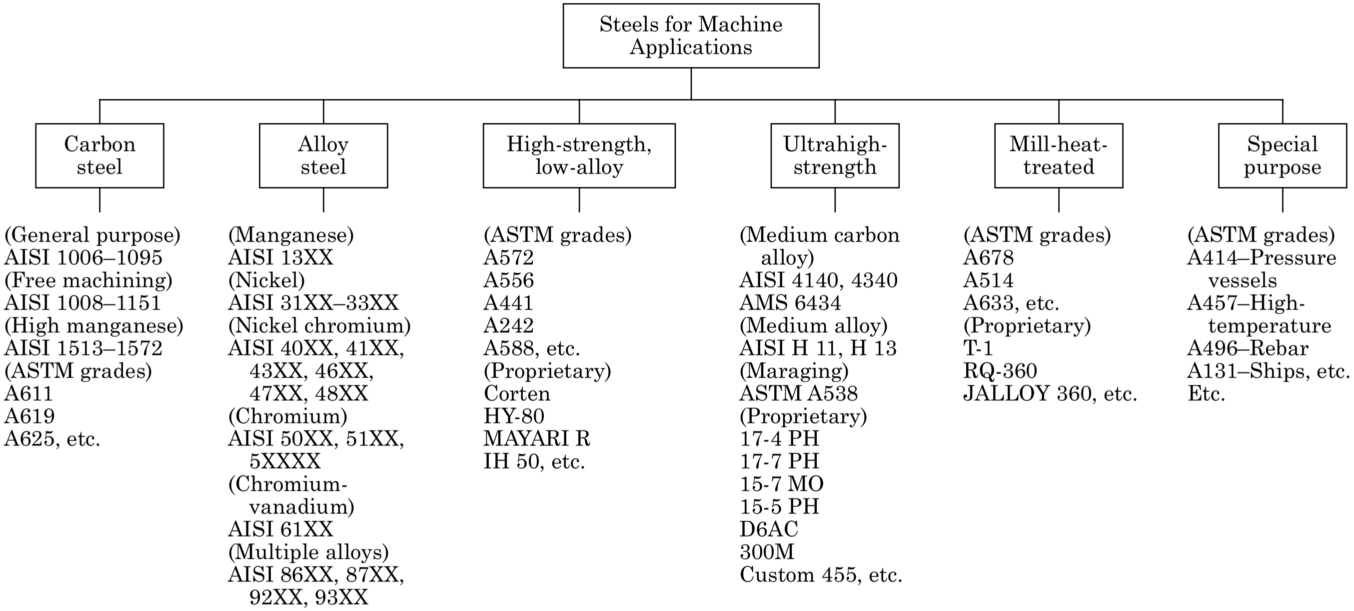

Figure 4.8 Steel types used for machine applications.[2]

TABLE 4.2 Major Groups in the AISI-SAE Designation System[2]

Class	AISI series	Major constituents
Carbon steels	10xx	Carbon steel
	11xx	Resulfurized carbon steel
Alloy steels		
Manganese	13xx	Manganese 1.75%
	15xx	Manganese 1.00%
Nickel	23xx	Nickel 3.50%
	25xx	Nickel 5.00%
Nickel-chromium	31xx	Nickel 1.25%, chromium 0.65 or 0.80%
	33xx	Nickel 3.50%, chromium 1.55%
Molybdenum	40xx	Molybdenum 0.25%
	41xx	Chromium 0.95%, molybdenum 0.20%
	43xx	Nickel 1.80%, chromium 0.50 or 0.80%, molybdenum 0.25%
	46xx	Nickel 1.80%, molybdenum 0.25%
	48xx	Nickel 3.50%, molybdenum 0;25%
Chromium	50xx	Chromium 0.30 or 0.60%
	51xx	Chromium 0.80, 0.95 or 1.05%
	5xxx	Carbon 1.00%, chromium 0.50, 1.00, or 1.45%
Chromium-vanadium	61xx	Chromium 0.80 or 95%, vanadium 0.10 or 0.15% min.
Multiple alloy	86xx	Nickel 0.55%, chromium 0.50%, molybdenum 0.20%
	87xx	Nickel 0.55%, chromium 0.50%, molybdenum 0.25%
	92xx	Manganese 0.85%, silicon 2.00%
	93xx	Nickel 3.25%, chromium 1.20%, molybdenum 0.12%
	94xx	Manganese 1.00%, nickel 0.45%, chromium 0.40%, molybdenum 0.12%
	97xx	Nickel 0.55%, chromium 0.17%, molybdenum 0.20%
	98xx	Nickel 1.00%, chromium 0.80%, molybdenum 0.25%

4.2.8.2 Stainless and specialty steels. Stainless steels are an important class of alloys used for a wide range of applications and in many environments. They are used extensively in the power generation, pulp and paper, and chemical processing industries, but they are also chosen for use in many everyday household and commercial products. They are iron-base alloys that contain a minimum of approximately 11 percent Cr, the amount needed to prevent the formation of rust in unpolluted atmospheres (hence the designation *stainless*). Few stainless steels contain more than 30 percent Cr or less than 50 percent Fe. Carbon is normally present in amounts ranging from less than 0.03 percent to over 1.0 percent in certain martensitic grades. Table 4.3 provides a useful summary of some of the compositional and property linkages in the stainless steel family.[10]

4.2.8.3 Magnetic steels. A wide range of magnetic characteristics are available from the many alloy combinations known to date. These magnetic characteristics are expressed in many specific parameters that have a significant meaning. To understand the information presented, one should be familiar with the general terms.

A general classification of magnetic alloys described herein is as follows:

1. High-permeability magnetic alloys
2. Permanent magnetic alloys
3. Stainless steel alloys
4. Temperature- compensator alloys

Magnetic parameters discussed here are typical for the respective alloy as determined by test methods having approval of ASTM Committee A-6, Magnetic Properties. An introduction to magnetic testing can be acquired by referring to ASTM Special Technical Publication 371, *Magnetic Testing: Theory and Nomenclature*. To discuss specific magnetic parameters of a given alloy, the method of test must be a standard test procedure that has been qualified by round-robin magnetic tests using an identical magnetic-core configuration. In cases for which a standard test does not exist, test methods must be identical, and the test equipment must be of identical circuitry. Reproducibility between test systems must be verified via the round-robin tests. This approach is employed in many instances between two or among several laboratories, because the ASTM standard methods of test do not provide all property information to predict performance in specific applications. Many nonstandard tests are employed today to express given properties in terms mutually agreed upon to express performance. These nonstandard test methods and procedures cover evaluations at all frequency levels, shapes of hysteresis loops, residual magnetism, types of magnetic field excitation, and the use of a selected magnetic-core configuration. If a magnetic core or magnetic-core section cannot be evaluated properly because of its shape, then a magnetic-core shape that is capable of being evaluated by standard methods of test can be subjected to the identical treatments. Standard magnetic tests will then provide property data in general terms.

Many magnetic materials, both high-permeability and permanent magnetic alloys, require thermal heat treatments or processes to achieve their designated optimal magnetic parameters. Each given magnetic material is capable of exhibiting a variety of magnetic properties as a result of heat treating and manufacturing processes; hence, it is necessary to specify details of heat treatment and test procedures. The manufacturing source must also control processing procedures so as to have minimal variation within a lot and from lot to lot.

TABLE 1.8 Martensitic, Austenitic, and Precipitation Hardening Alloys [6]

	Martensitic alloys
420	The basic martensitic alloy; corrosion resistant only in the hardened condition
410	Lower carbon content version of 420
440C	Higher carbon content version of 420; very hard and abrasion resistant
440A and 440B	Lower carbon content version of 440C; trades off some hardness to reduce brittleness
416	A free-machining variation of Type 410
420F and 440F	Free-machining variations of 420 and 440 C
430F	Free-machining variations of 430
430Ti	A small amount of titanium to is added to 430 to suppress all hardening during exposure to elevated temperature
	Austenitic alloys
302	The basic austenitic alloy containing 18% Cr and 8% Ni
304	Lower carbon content version of 302; better weldability and corrosion resistance
321, 347, 348	Type 302 with additions of titanium or columbium. The function of these added elements is to tie up all the carbon in the alloy so it cannot precipitate as chromium carbide. The columbium carbide is more stable than the titanium carbide (that is, more insoluble at higher temperatures), and for that reason the columbium alloy will withstand more severe conditions than Type 321.
304L	Even lower carbon version of Type 302, but still susceptible to sensitization; 0.03% C max.
303 and 303Se	Modifications of 302, to which sulfur or a combination of phosphorus and selenium are added to improve the machinability
302B	Type 302 with an addition 2% silicon; has a maximum operating temperature of 1800°F
308	Used mainly as a welding wire used to deposit an 18-8 analysis in the weld, allowing for some dilution during welding
310	The grade with the highest chromium content, chiefly known for its high scaling resistance
316, 316L, 317, 317L	Type 316 is generally considered to be the most corrosion resistant of all stainless steels. However, even Type 316 is considered borderline corrosion resistant when exposed to certain chemicals. An increase in the molybdenum content of approximately 1% (317) is believed to provide pitting and general corrosion resistance. Both of these molybdenum-bearing stainless steels find many applications requiring welding. 316L and 317L are the extra low carbon grades produced for these applications.
301	The corrosion-resistant grade includes a lower carbon level and a small increase in columbium to eliminate sensitization. The presence of copper improves the corrosion resistance in phosphoric acid solutions especially.
305	Low work-hardening rate alloy for cold-heading applications
201 and 202	200 series alloys were developed to conserve nickel during a time of nickel shortage. By substituting increased amounts of nitrogen and manganese for some of the nickel, it is possible to arrive at an analysis that has engineering properties very similar to the 300 series. The 200 series steels have slightly higher high-temperature strengths and room-temperature hardness due to the nitrogen. They also have higher work-hardening rates and are slightly less corrosion resistant.

TABLE 1.8 Martensitic, Austenitic, and Precipitation Hardening Alloys (Continued)[6]

Precipitation-hardening alloys	
17-4PH	The advantages of utilizing this precipitation hardening method rather than the phase change used in Type 410 include freedom from heavy scaling, freedom from warpage, and excellent surface quality, undamaged by heat treatment. In addition 17-4 PH exhibits corrosion resistance that is definitely superior to the Class I alloys and is equivalent to 18-8 in most corrosion environments.
17-7PH and PH 15-7 Mo	These semiaustenitic steels are austenitic at room temperature when they have been solution annealed at 1900–2000°F and rapidly cooled. As such, they are soft and ductile and can be formed or drawn. As with 17-4 PH, the hardness immediately after transformation is relatively low: Rockwell C 30. The final heat treatment once again consists of an aging or precipitation hardening heat treatment at 950–1150°F, and hardness from Rockwell C 38 to C 49 is possible. The precipitation hardening is achieved by the addition of about 1% aluminum. 17-7 PH serves in many general applications. In PH 15-7 Mo, the chromium was replaced with molybdenum to achieve higher creep and rupture strengths in the temperature range of 700–1000°F.

4.2.9 High-permeability magnetic alloys

High-permeability magnetic alloys, also known as *soft magnetic alloys*, are required to have low magnetic hysteresis loss resulting from variations in the magnetic flux density produced within the alloy and a low residual magnetism after being subjected to a high magnetic field strength. This class of alloys does not retain permanent magnetic poles to any significant degree after being highly magnetized. Several alloy families produce magnetic properties that are of interest to the industry. Within each family, specific alloy compositions have been selected by the industry as standard grades because of best magnetic properties for a large number of applications.

4.2.9.1 Nickel-iron alloys. This family of alloys contains 30 to 80 Ni, with the balance Fe, and exhibits a variety of magnetic and expansion properties. In some cases, small percentages of other elements are added to obtain more desirable magnetic properties for certain applications. Figure 4.9 shows the effect of nickel content on initial permeability and Curie range and Curie points. All the nickel-iron alloys used for magnetic properties contain low carbon and cannot be hardened or have their hardness increased by thermal heat treatment. Hardness can be increased only by cold-working the alloy, and the higher the hardness, the lower the high-permeability characteristics. Thermal heat treatment will reduce the hardness, and the lower the hardness, the higher the high-permeability characteristics will be. Hardness, however, in the softest condition, is no reflection on the degree of optimal high-permeability melt to melt, or lot to lot from the same melt.

Producers of steel-mill products do not supply the alloys in the high-permeability condition in forms of bar and strip, because subsequent fabrication operations such as machining, bending, forming, and deep drawing reduce the high-permeability properties by the introduction of cold-work stresses. Parts

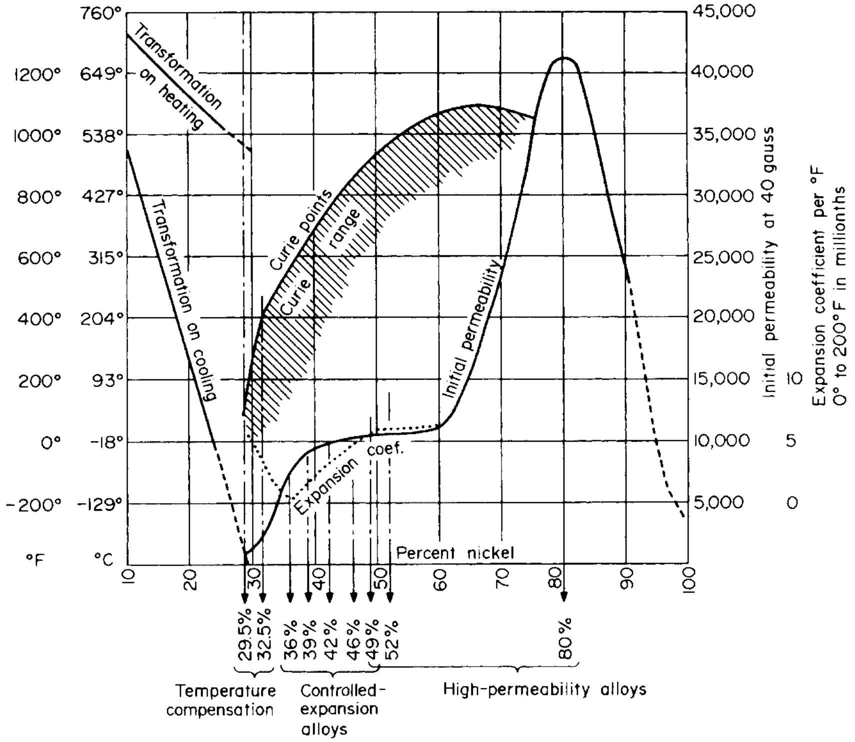

Figure 4.9 Effect of nickel content on magnetic and expansion properties of some high nickel-iron alloys.

must be subjected to the thermal heat treatments to achieve most uniform desired magnetic properties.

High-permeability materials can be purchased in several types of physical conditions for easiest fabrication, depending on the part to be made.

Suggested physical conditions are as follows:

- Blanking of flat parts—Rockwell B-90 minimum
- Blanking and forming—Rockwell B-75/85
- Best forming or deep drawing—Rockwell B-75 maximum

Each alloy is capable of exhibiting a variety of magnetic properties. Lowest magnetic properties are observed in the cold-work or high-hardness condition; hence, any thermal heat treatment relieving cold-work stresses will improve the magnetic characteristics over those originally shown. Heat treatments should be conducted in a nonoxidizing, noncarburizing, noncontaminating atmosphere.

Atmospheres generally employed are dry hydrogen, dissociated ammonia, argon, dry nitrogen, and vacuum. It is recognized that the best atmosphere is dry hydrogen. The heat treatment is conducted in a sealed retort or equivalent. A continuous flow of atmosphere in the retort ensures the removal of undesirable gas compounds given off by the alloy, and this helps to improve the magnetic quality. Elements removed from the alloy are carbon, oxygen, and sulfur. It is necessary to study the magnetic properties of the heat-treated parts by varying temperature, time at temperature, and cool rate for establishing the treating procedure for a given facility.

Recommended heat treating for highest permeability in the nickel-iron family of alloys is as follows:

1. The retort should be capable of being gas tight or vacuum tight: i.e., a sealed retort.
2. Purge or flush the retort to free it of ambient atmosphere.
3. Introduce a protective or purifying atmosphere.
4. Heat the retort to 1120 to 1170°C.
5. Hold 2 to 4 hr at temperature.
6. Cool at a rate recommended for the alloy.
7. Use a protective or purifying atmosphere until the chamber is cooled to 200°C or less.
8. Introduce an inert atmosphere until cooled below 100°C.
9. Open the retort.

Typical magnetic properties of the most common high-permeability alloys are given in Table 4.4. Recommended heat treatments for obtaining these magnetic properties are shown for each alloy. These data apply to cold-rolled strip items of 0.030 in or thicker and bar items. Figure 4.10 provides the normal induction curves for the various alloys.

Alternating-current magnetic properties vary considerably, depending on lamination thickness, degree of interlaminar resistance, lamination shape, and frequency of the magnetizing current. Because each alloy exhibits a wide variety of AC magnetic characteristics, each commercial grade will be reviewed separately.

4.2.9.2 80 Ni, 4 Mo, balance Fe. This alloy is recognized as one of the highest initial permeability alloys and is used for its response to very low magnetizing forces. Trade names are 4-79 Permalloy[1] HyMu 80[2] and Hipernom.[3]

Magnetic-core and lamination manufacturers have applied various other brand names to the alloy. The most common application for this alloy is in the form of laminations 0.006 and 0.014 in. thick; hence, 60 and 400 Hz data are readily available. See Figs. 4.11 and 4.12 for typical data. Core loss data are given in Fig. 4.13. The alloy is available in strip form as thin as 1/8 mil (0.000125 in), which is used to manufacture small bobbin cores having specific square hysteresis-loop properties. Thicknesses in the range of 0.5 to 4 mils are used to manufacture numerous types of magnetic cores such as tape toroids

TABLE 4.4 Typical DC Magnetic Properties of Some Nickel-Iron Alloys

Property	45 Ni, bal. Fe	49 Ni, bal. Fe	49 Ni, 0.15 Se, bal. Fe	47 Ni, 3 Mo	78.5 Ni, bal. Fe	77 Ni, 1.5 Cr, 5 Cu	80 Ni, 4 Mo	80 Ni, 5 Mo
Heat treatment, Hz	←1140/4/1→				1040/2/ 600 Q	1140/4/1	←1140/4/5→	
B_{40} permeability	5,000	7,000	3,200	4,000	8,000	20,000	50,000	70,000
Max. permeability	60,000	75,000	10,000	70,000	120,000	150,000	200,000	150,000
Approx. B at max. permeability	8,000	7,000	6,000	5,000	3,000	3,000	3,500	3,500
Coercive force, oersted	0.07	0.04	0.25	0.08	0.02	0.02	0.01	0.009
From B, gauss	10,000	10,000	10,000	10,000	10,500	5,000	7,000	7,000
Saturation induction, gauss	15,000	15,500	15,000	163,500	13,000	6,500	7,700	8,500
Curie temp., °C	460	500	500	460	600	400	460	450
Electrical resistivity, μΩ-cm	45	48	48	80	20	60	58	63
Density, g/cc	8.17	8.25	8.25	8.27	8.45	8.50	8.74	8.75

Q = quench from temperature.
Heat treatment: 1140°C for 4 hr at temperature; 1°C/min cool rate (1140/4/1).

for high initial permeability and tape toroids having square hysteresis loop characteristics. Typical magnetic properties of strip at thicknesses of 1, 2, and 4 mils are given in Table 4.5.

TABLE 4.5 Typical Magnetic Properties of 80 Ni, 4 Mo, Balance Fe

		1-, 2-, and 4-mil square loop properties*				
Thickness, in	B_{40} @ 60 Hz	B_m, gauss	$B_m - B_r$, gauss	H_1, oersteds	ΔH	μ @ B_{40} and 15 kHz†
0.001	70,000	7,000	1,000	0.030	0.006	20,000
0.002	80,000	7,000	1,200	0.030	0.006	12,000
0.004	80,000	7,000	1,500	0.035	0.009	

*Constant-current, flux-reset method of test per AIEE No. 432. Heat treatment: 1160°C for 0.5 hr at temperature, 1–5°C/min cool rate.
†Heat treatment: 1170°C for 1–4 hr at temperature; 5–15°C/min cool rate. Tape toroid ID/OD 0.80 ratio.

As stated previously, a wide variety of magnetic characteristics are obtainable by various heat treatments, as shown by 0.006-in lamination strip in Fig. 4.14. The magnetic properties will also be altered by time at temperature and

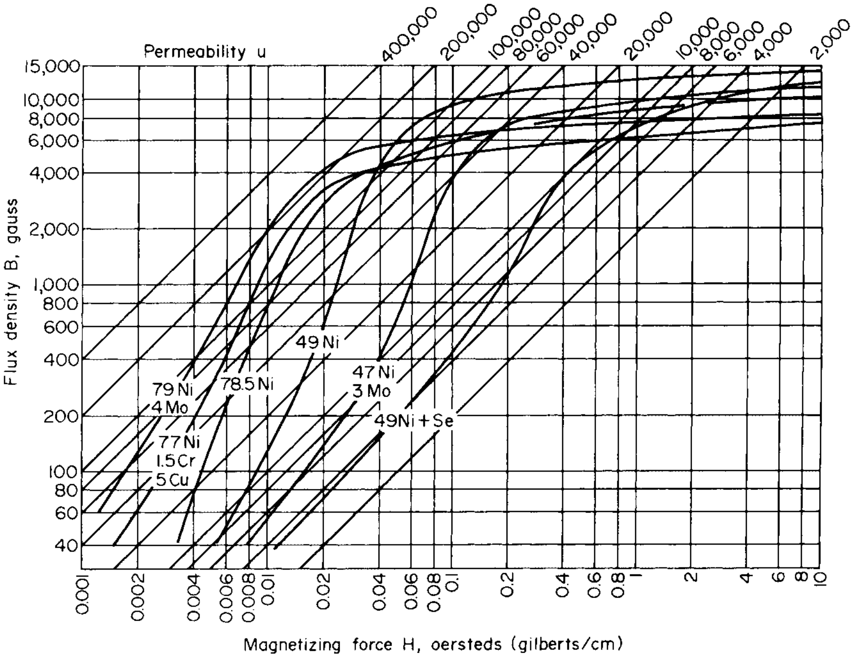

Figure 4.10 DC normal induction curves for some nickel-iron alloys.

cool rate; i.e., in some cases, magnetic-core parts are heat treated through the continuous furnace and produce acceptable magnetic properties for the given application. Because the alloy shows a very low hardness value (Rockwell B 50/55) after heat treatment, parts cannot be stressed or deformed without a loss and change in magnetic properties. Extreme care must be exercised during handling. Magnetic-core parts heat treated at lower temperatures are less strain sensitive.[4] General literature on other basic magnetic properties is available from the alloy producers in the U.S. such as Carpenter Technology.

4.2.9.3 77 Ni, 1.5 Cr, 5 Cu, balance Fe. This alloy has high initial permeability properties and is well known as Mumetal.[1] Its handling characteristics are similar to those of the 80 Ni, 4 Mo, balance Fe alloy. General magnetic characteristics for laminations, magnetic cores, and shields are available from the producer.

4.2.9.4 49 Ni, balance Fe. The alloy composition of 49 Ni, balance Fe is capable of producing a fairly high initial permeability with a moderately high magnetic saturation. Magnetic-core components are used where response is necessary in a fairly weak magnetic field; they have minimum residual magnetism where very small air gaps are in the magnetic circuit and show fairly good properties in AC magnetic fields. General usage is in the form of lamination strip, fabricated relay parts, and flux-carrying members and precision

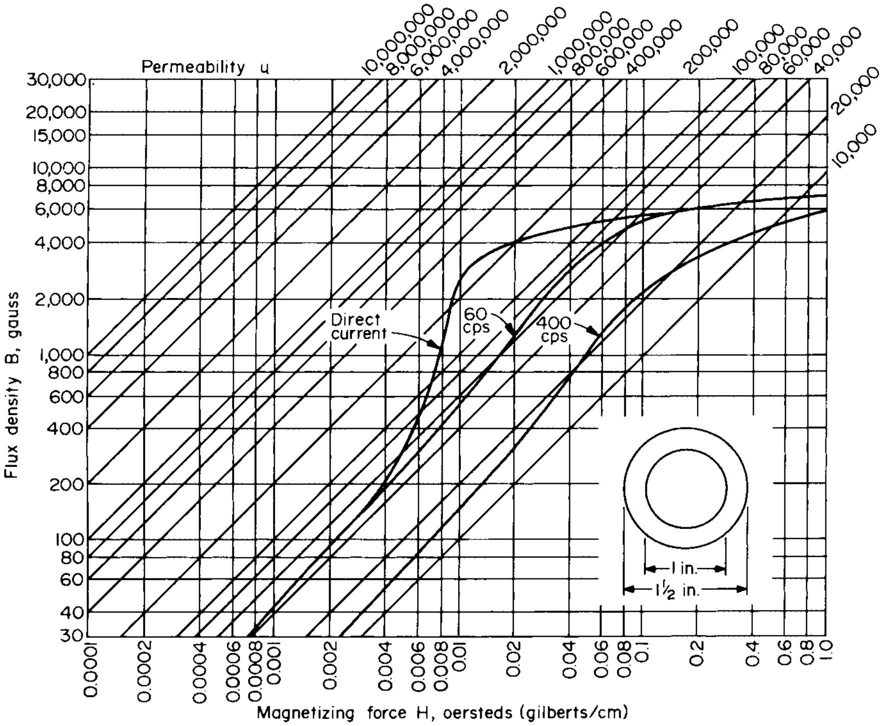

Figure 4.11 DC and AC magnetic properties of 80 Ni, 4 Mo, balance Fe lamination strip, 0.014 in thick.

castings. A free-machining grade is available; however, there is a substantial sacrifice in the magnetic properties.

Through controlled melting practice and strip manufacturing procedures, several types of strip products are available in the industry to achieve specific types of magnetic properties that can be utilized in specific types of magnetic cores. This applies to strip products 0.020 in and less. The strip products are referred to as highly oriented, semioriented, and random-oriented. In each case, the strip product must be fabricated and heat treated as recommended to achieve the magnetic properties desired.

The semioriented grade is preferred for transformer lamination applications, because it has the highest magnetic properties when heat treated above 1000°C. Lamination strip AC properties are given in Figs. 4.15 and 4.16. Core-loss values appear in Table 4.6.

The random-oriented grade is recommended for rotor and stator laminations that must have minimal directional magnetism. The most suitable method of detecting this grade is a very fine grain size when heat treated at 1100°C (mean grain diagonal of 0.040 in). The semioriented grade will show a very coarse grain when heat treated under similar conditions. Basic magnetic properties of the random-oriented grade are slightly lower than those of the semioriented grade; however, they are superior to those of the semioriented

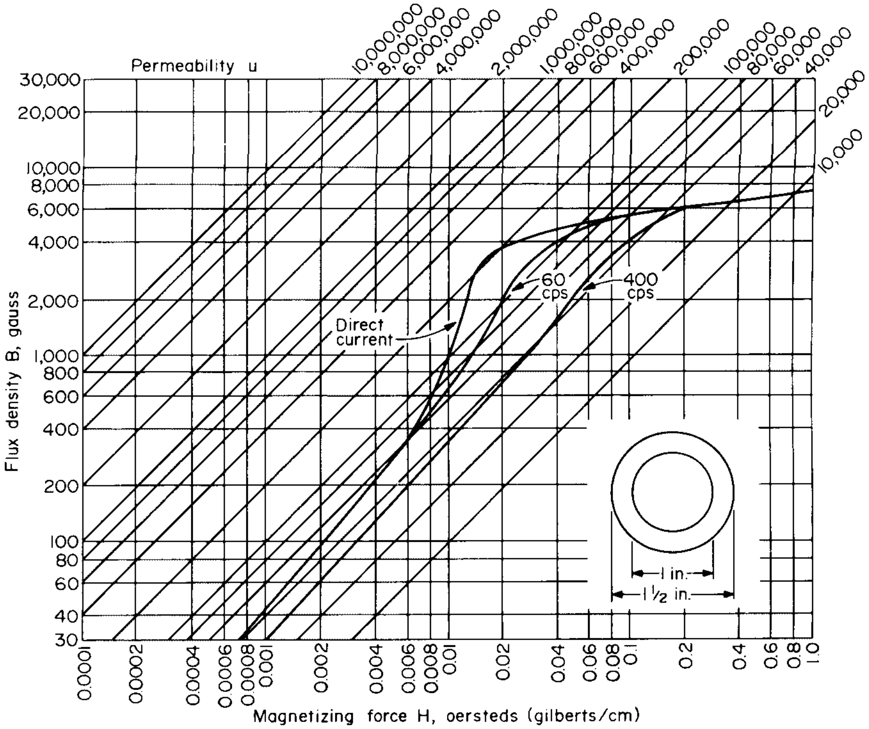

Figure 4.12 DC and AC magnetic properties of 80 Ni, 4 Mo, balance Fe lamination strip, 0.006 in thick.

grade when heat treated below 1000°C. The effect of temperature on magnetic properties is shown in Fig. 4.17.

Highly oriented 49 Ni, balance Fe is marketed in strip form, from 0.5 to 14 mils, and is used for its square hysteresis loop properties after heat treating the fabricated cores. Laminations 0.006 and 0.014 in thick are available for certain types of magnetic cores.

Soft magnetic alloys are employed to shield magnetic components and electron beams from undesirable external magnetic fields that affect their function. This is accomplished by utilizing the soft magnetic alloy to deflect or carry around the undesirable magnetic field. Shields can also be used to contain undesirable magnetic fields by surrounding the undesirable source. Shielding efficiency in dB, a function of the magnetic alloy thickness, magnetic permeability, and shape of the shield, can be calculated for long, thin cylinders, using the equation

$$\text{S.E.} = 20 \log 1 \mu t / 2R_o \qquad (4.1)$$

where μ = permeability
t = thickness
R_o = outer radius of shield

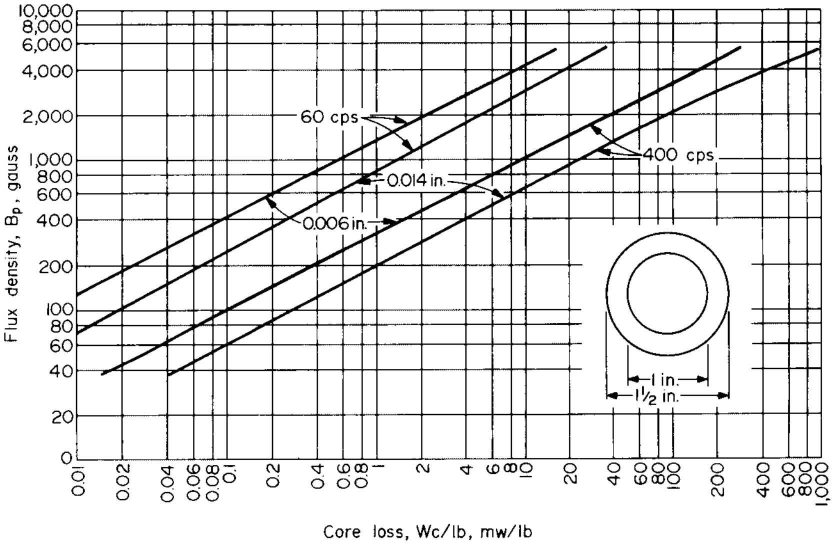

Figure 4.13 Core loss of 80 Ni, 4 Mo, balance Fe lamination strip.

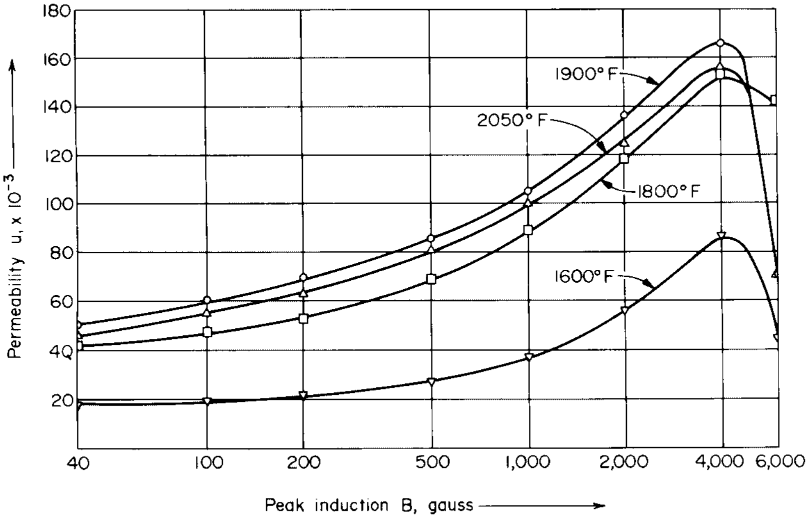

Figure 4.14 AC permeabilities vs. induction at 60 Hz for 80 Ni, 4 Mo, balance Fe, 0.006-in stamped rings for various 4-hr anneals.

This equation can be useful in determining how much the shield dimensions should be modified to compensate for a change in shield material permeability.

Laminated shields provide greater efficiency. To protect from very high-frequency fields, copper and soft magnetic alloy laminates are employed. Specific information regarding magnetic shielding is presented in Ref. 11.

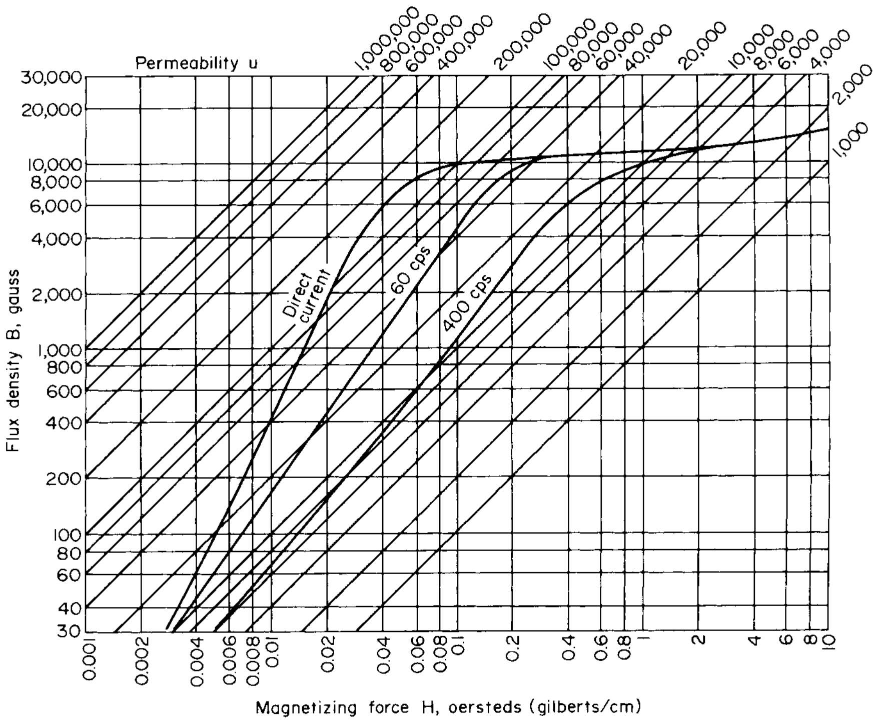

Figure 4.15 DC and AC magnetic properties of 49 Ni, balance Fe semioriented lamination strip, 0.014-in strip.

4.2.9.5 Silicon-iron alloys. The family of silicon-iron alloys has a very important role in the field of magnetics because of their low cost and because of having been engineered into systems wherein an appreciable amount of electric power is involved. Even though their response to weak magnetic fields is inferior to that of the nickel-iron alloys, their magnetic characteristics surpass those of other alloys in the field of electronics under certain conditions. A considerable amount of property evaluation has been conducted for the electrical industry, and electric core-loss requirements have been established for the electrical sheet industry. Basic magnetic requirements of commercial grades are given in Ref. 11.

Three types of silicon-iron alloys in thick strip and bar forms are being fabricated into many shapes of magnetic cores and magnetic flux-carrying members. Machining operations, forgings, and precision castings make all shapes and sizes available. Commercial available grades have nominal silicon contents of 1, 2.5, and 4 percent. For improved machining properties, the silicon contents of 1 and 2.5 percent are available in free-machining grades. As with all other high-permeability alloys, a thermal heat treatment is required to obtain uniform magnetic properties from part to part. Magnetic properties improve with increasing heat-treating temperature.

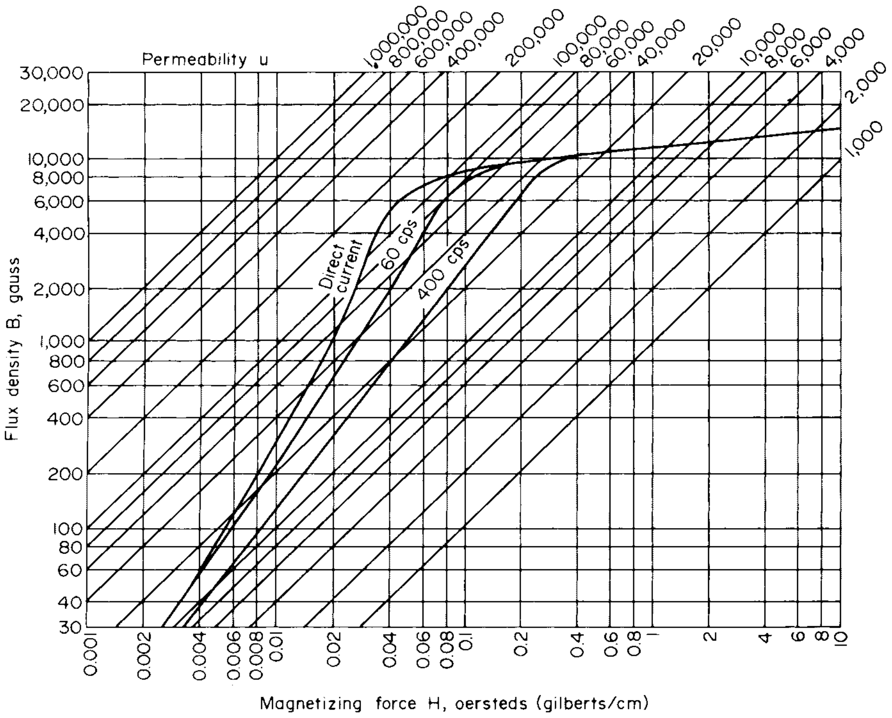

Figure 4.16 DC and AC magnetic properties of 49 Ni, balance Fe semioriented lamination strip, 0.006-in strip.

4.2.9.6 Cobalt-iron alloys. The family of cobalt-iron alloys and the various elements added to this family have been thoroughly investigated for basic magnetic properties.[5,6] Five basic alloys have found commercial application; however, only three are being manufactured in production quantities in various forms. These alloys are used primarily for their high magnetic saturation and relative low coercive force in AC and DC applications. Typical magnetic properties are given in Fig. 4.18.

4.2.9.7 Commercial irons and commercially pure irons. Many commercial irons are used for their magnetic properties because of their relative low cost in comparison to other, more expensive nickel-iron, silicon-iron, and cobalt-iron alloys. The magnetic properties obtainable vary considerably, depending on the heat treatment applied to the fabricated parts. Magnetic data on these alloys are very limited, as the properties are not too critical.

Applications requiring a minimal degree of nonmetallics and freedom of internal discontinuities demand a product that is manufactured by other procedures, such as consumable electrode melting and/or vacuum-induction melting. These methods of manufacture also ensure a very low carbon con-

TABLE 4.6 Core Loss of 49 Ni, Balance Fe "Semioriented" and "Random-Oriented" Strip (60-Hz Core Loss, mW/lb)

°C for 4 hr	B, gauss 1,000	2,000	4,000	6,000	8,000	10,000
	0.006-in rings, semioriented grade					
920	9.60	26.3	68.5	120.0	173.0	240.0
982	2.66	8.45	26.6	52.0	85.5	135.0
1038	1.83	6.03	19.7	39.8	66.6	107.0
1093	1.51	5.20	17.8	36.4	60.0	101.0
1180	1.58	5.43	18.2	37.4	66.1	103.0
	0.006-in rings, random-oriented grade					
870	6.21	18.5	67.0	85.7	131.3	193.0
920	4.42	13.44	51.5	66.8	104.1	154.5
982	3.26	10.2	41.8	54.8	86.5	131.6
1180	2.07	6.98	31.6	42.7	72.4	112.3
	0.014-in rings, semioriented grade					
920	9.95	28.0	74.3	132.0	195.0	275.0
982	3.02	9.85	31.1	62.5	107.0	174.0
1038	2.69	8.91	28.8	58.0	99.9	164.0
1093	2.47	8.50	27.9	57.0	99.0	162.0
1180	2.64	8.90	28.6	57.6	99.5	164.0
	0.014-in rings, random-oriented grade					
920	5.34	16.2	62.2	82.1	130.9	199.2
982	4.20	13.2	53.9	72.4	119.2	185.0
1180	3.61	8.97	40.2	55.0	93.3	151.3

tent, lowest gas content, and minimal residual elements. Their characteristics ensure the best performance in vacuum envelopes and minimal contamination over long periods of time.

With regard to mechanical properties and suggested machining information for magnetic alloys, general information has been compiled for some of the alloys reviewed. Thermal expansion properties are given in Table 4.7.

4.2.9.8 Permanent magnetic alloys. Permanent magnetic alloys are generally referred to as *hard magnetic materials*. These materials retain magnetic poles (north and south) after being subjected to a strong magnetic field. Magnetic property tests are generally conducted on specific bar shapes that have been heat treated. Most common magnetic parameters employed to compare and rate permanent magnetic materials are the following:

1. *Coercive force, H.* The demagnetizing force that must be applied to a magnet to reduce the magnetic induction to zero.

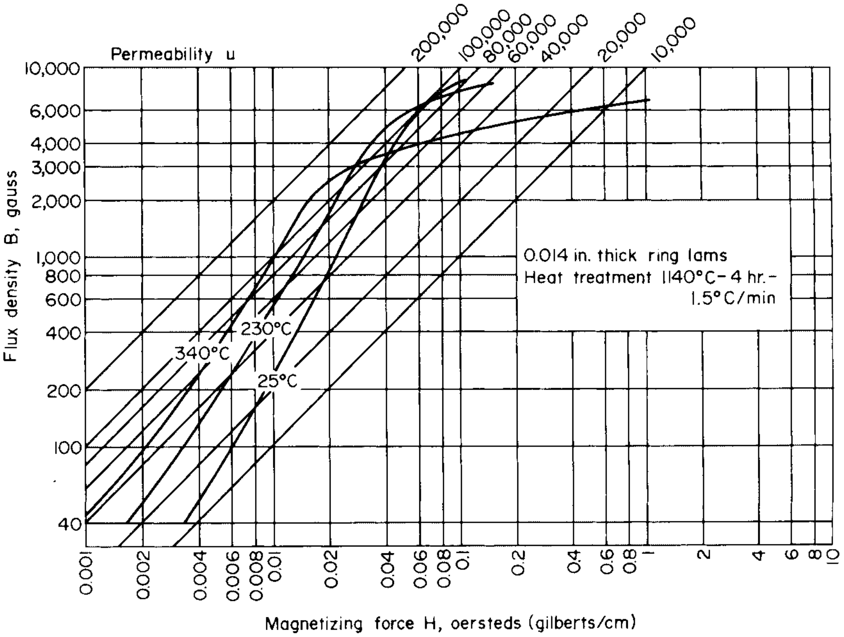

Figure 4.17 60-Hz permeability vs. temperature for 49 Ni, balance Fe random-oriented alloy.

TABLE 4.7 Thermal Expansion Properties of Some Magnetic Alloys*

Temp., °C	80 Ni, 4 mo, bal. Fe	77 Ni, 1.5 Cr, 5 Cu, bal. Fe	49 Co, 2 V, bal. Fe	27 Co, bal. Fe	1 Si, bal. Fe	2.5 Si, bal. Fe	4 Si, bal. Fe	Commercial iron
20–100	11.51	12.5	—	—	11.2	11.3	11.8	12.7
200	12.62	14.4	—	10.10	12.0	12.2	12.4	13.8
300	13.20	—	9.5	10.35	12.4	13.2	12.9	14.6
400	13.67	—	—	—	12.8	—	13.5	15.8
500	13.95	—	9.8	10.90	—		—	16.7

*Coefficient of expansion = in/in × 10^{-6}/°C.

Note: Information for 36 Ni, bal. Fe and 49 Ni, balance Fe can be found in the text.

2. *Demagnetization curve.* The second-quadrant portion of the hysteresis loop relating induction in a magnet to its magnetizing force.

3. *Energy product, BH_{max}.* The product of B × H in the second quadrant of the hysteresis loop. A figure of merit for a magnet. It is proportional to the amount of external energy available from a magnet of given dimensions.

4. *Residual induction, B_r.* The magnetic induction that is retained by a magnet after removal of a saturating magnetizing force.

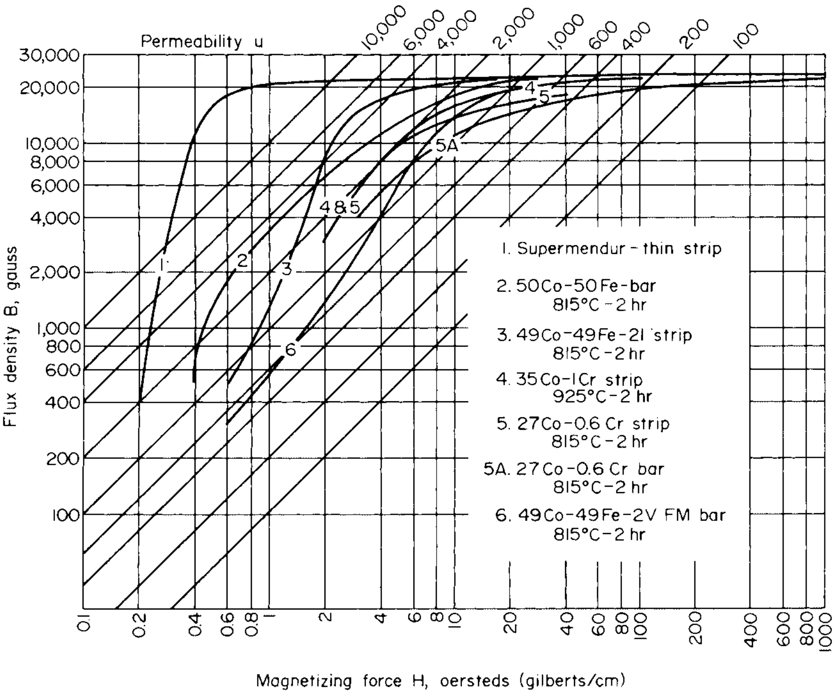

Figure 4.18 DC normal induction curves of Fe-Co alloys.

5. *Intrinsic curve (B – H).* A plot of intrinsic induction in the second and third quadrants of the hysteresis loop. Intrinsic induction is not zero at the H_c point. This means that a field intensity H that is large enough to hold B at zero does not completely demagnetize the magnet, because of recoil. Complete demagnetization occurs only when $B - H = 0$.

Many alloy compositions have been evaluated for their permanent magnetic characteristics; however, the industry has standardized on certain compositions to meet the general requirements. Cobalt and chromium steels are available in wrought (rolled) and cast shapes. When permanent magnet units are very small (less than several ounces), the sintering manufacturing procedure may be preferred for economic reasons and to obtain higher physical properties. Because permanent-magnet alloys are very hard in the heat-treated condition, the unit cannot be machined or formed. Metal removal can be achieved only by grinding operations, and these must be conducted very carefully so as not to fracture the unit.

Ferrite magnets are also known as *ceramic magnets.* General composition is of a, $M \cdot 6Fe_2O_3$, where the M represents barium, strontium, lead, or combinations thereof. This type of magnet is very hard and brittle, is a good electrical insulator and a poor conductor of heat, and is chemically inert. Careful grinding procedures are recommended for removing material. Considerable development work is in progress on this type of permanent-magnet material, and it is necessary to maintain constant contact with producers to ascertain new products commercially available.

4.2.9.9 Stainless steels. Stainless steels are divided into two groups: ferritic stainless steels (400 series) and austenitic stainless steels (300 series). Ferritic stainless steels are magnetic and can be further subdivided into martensitic (hardenable) and ferritic (nonhardenable) groups. Types 410, 416, 420, and 440 can be hardened by heat treatment and, in this condition, the alloy acts as a weak permanent magnet, as illustrated in Table 4.8 by the H_c values. In the full-annealed (low-hardness) condition, the magnetic values are considered to be weak, soft magnetic properties. Table 4.9 lists the general magnetic properties and includes the ferritic grades such as Types 430, 430F, and 446.

TABLE 4.9 Typical DC Soft Magnetic Properties of Type 400 Stainless Steels

Types	Hardness, Rockwell B	μ at B gauss 500	1,000	5,000	10,000	μ_{max}	H_c, oersteds from 10^3 gauss
410 and 416*	80	200	380	900	1,020	1,080	5.0
430 and 430 F	75	400	550	1,600	1,600	1,840	1.7
446†	85	350	500	1,100	700	1,100	4.0

*Heat treated at 815°C for 2 hr, furnace cooled.
†Heat treated at 900°C for 2 hr, furnace cooled.

Type 400 series stainless steels are employed for their magnetic properties when other soft magnetic alloys lack corrosion resistance to a given media and plated cores cannot be employed. Type 400 series stainless steels provide corrosion resistance to fresh water, mine water, steam, gasoline, crude oil, perspiration, alcohol, ammonia, soap, sugar solutions, and most foods.

Austenitic stainless steels (Type 300 series) are generally considered to be nonmagnetic alloys having good corrosion resistance to ambient conditions. All Type 300 series stainless steels have maximum permeabilities of 1.005 or less in the annealed (lowest hardness) condition. Cold work introduced through processing and fabrication will increase the maximum permeability. The rate of increase depends on the chemical composition and the stability of the austenite.[7]

4.2.9.10 Temperature-compensator alloys. As the nickel content in nickel-iron alloys increases above 29 percent, the Curie temperature increases (see Fig. 4.9). Commercial alloys containing 29 to 39 percent nickel are utilized as temperature-compensator alloys, because their magnetic saturation decreases with increasing temperature. This characteristic provides a means of controlling a DC magnetic flux density produced by a permanent-magnet or an electromagnet field which decreases with increasing temperature. To achieve this performance from the temperature-compensator alloy, the magnetic source must produce a magnetic flux density in the alloy above the knee of the DC (B – H) curve. Most data available for these alloys have been determined at 46 oersteds, which is in the saturation range.

Generally, the magnetic pole strength of a permanent magnet decreases with increasing temperature. To achieve a uniform functional magnetic field, the temperature-compensating alloy is employed to shunt magnetic lines of force from the poles and away from the functional magnetic area. As the temperature decreases and the magnet pole strength increases, the compensating alloy shunts or robs more flux from the functional area. With increasing temperature and decreasing magnet pole strength, the compensating alloy shunts less flux. By proper selection of compensating alloys, thickness of the compensator cross section, and design of the shunt, the functional magnetic field can be controlled.

The temperature-compensating characteristics of these alloys can be varied by the amount of cold-work stresses introduced into the alloy. Cold work decreases the flux-carrying capacity and reduces the change in flux density per degree of temperature from that shown by the alloy in the annealed condition (condition generally supplied by the producer). Thermal treatments up to 480°C for several hours help to make the properties more stable with time and increase the flux-carrying capacity slightly. If the degree of cold work exceeds 10 percent reduction, it is recommended that the part be heat treated as recommended by the producer.

Temperature-compensator alloys are used to compensate permanent magnets in instruments, switches, watt-hour meters, tachometers, speedometers, microwave tubes, and so forth. These alloys can also be used for thermal switches and temperature regulators. Nominal flux density changes with temperature of commercial grades are given in Table 4.10.

TABLE 4.10 Magnetic Flux Densities vs. Temperature of Temperature-Compensating Alloys at *H* = 46 Oersteds

Ni content, %	29.0	29.8	29.8	32.5	36.0	38
Type*	5	4	2	1		
Temperature, °C	Flux density, gauss					
–60	—	—	—	10,450	14,900	—
–40	4,000	5,450	5,650	9,900	14,400	—
–20	2,980	4,620	4,900	9,350	—	—
0	1,350	3,480	3,920	8,700	13,400	14,200
15	370	2,500	3,000	—	—	—
25	148	1,760	2,240	7,800	12,700	13,400
40	40	750	1,120	7,250	—	—
50	—	340	550	—	11,870	13,200
80	—	—	—	5,450	10,700	—
90	—	—	—	4,800	10,500	—
100	—	—	—	—	10,000	12,000
150	—	—	—	—	7,000	9,200
200	—	—	—	—	—	8,800

*Carpenter Technology Corp. type numbers.

4.2.10 Thermal expansion properties of alloys

Many ferrous alloys are used in various applications for their thermal expansion characteristics. All metals expand when the temperature is increased above 25°C (77°F) and contract when the temperature is decreased. The rate of expansion and contraction depends on chemical composition and physical condition; hence, a wide variety of thermal expansion characteristics are available from ferrous alloys. Typical thermal expansion properties of various alloys employed in the industry for this particular characteristic will be reviewed. Test procedures have been established by ASTM to determine the expansion characteristics of materials. Thermal expansion properties are typically expressed as the change in length per unit length resulting from a change in temperature of the material.

Data presented herein are expressed in the form of mean (average) coefficient of linear expansion in units per degree Fahrenheit. These data can be employed to calculate and plot the linear thermal expansion. From the linear thermal expansion, the instantaneous coefficient of linear thermal expansion can be determined.

4.2.10.1 Nickel-iron alloys and related alloys. This family of alloys has been thoroughly investigated for thermal expansion properties. The alloy containing 36 Ni, balance Fe (Invar) exhibits the lowest expansion properties of all metals (see Fig. 4.9); hence, the 36 percent nickel alloy is used predominantly in applications wherein minimum size change is necessary. The dimensional stability with time and thermal heat treatment to achieve same has been thoroughly investigated.[12] Investigations are in progress to reduce the expansion properties further by controlling the residual elements commonly found in commercial alloys. A free-machining grade, having slightly higher expansion characteristics, is available to realize lower machining cots. Invar itself is difficult to machine because of the gumminess of the alloy.

Figure 4.9 illustrates that, as the nickel content decreases below 36 percent and increases above 36 percent, the 25°C (77°F) coefficient of expansion increases; however, with increasing nickel content up to 65 percent, the Curie temperature increases. Below the Curie temperature, the nickel-iron alloys show fairly uniform coefficients of expansion; however, in the Curie range, the expansion properties increase. Above the Curie temperature, the alloys expand at a very rapid rate—similar to a true austenitic alloy having an instantaneous coefficient in the range of 9 to 10×10^{6}/°F. To achieve specific expansion properties, other elements can be added, such as chromium. The addition of other elements increases the coefficient of expansion and lowers the Curie temperature. Expansion properties and physical properties of standard commercial grades are given in Table 4.11.

Expansion data, except for 36 Ni, balance Fe, are given for the annealed condition (free of cold-work stresses by heat treating at 1925°F for 2 hr in a nonoxidizing atmosphere). Expansion characteristics in conditions other than annealed are not reproducible, and they change as cold-work stresses are relieved.

TABLE 4.11 Thermal Expansion and Physical Properties of Nickel-Iron Alloys and Related Alloys

Type analysis and properties	36 Ni	36 Ni, FM	39 Ni	42 Ni	42 Ni, 6 Cr
Carbon[*]	0.03	0.05	0.05	0.03	0.06
Manganese	0.35	0.90	0.40	0.50	0.50
Silicon	0.30	0.35	0.25	0.25	0.25
Nickel	36.0	36.0	39.0	42.0	42.5
Other elements	—	Se 0.20	—	—	Cr 5.75
Iron	bal.	bal.	bal.	bal.	bal.
Physical constants					
Specific gravity	8.05	8.05	8.08	8.12	8.12
Density, lb/in^3	0.291	0.291	0.292	0.293	0.294
Thermal conductivity, Btu/(hr)(ft^2)(°F/in)	72.6	72.6	73.5	74.5	87.0
Electrical resistivity, Ω/cir mil-ft	495	495	440	430	570
Curie temperature, °F	536	536	644	716	563
Specific heat, Btu/(lb)(°F)	0.123	0.123	0.121	0.120	0.120
CTE, in/in × 10^{-6}/°F (annealed)					
At 77–212°F	0.655[†]	0.89[‡]	1.22	2.57	3.64
392	0.956	1.62	1.48	2.54	3.94
572	2.73	3.33	1.88	2.71	4.59
662	3.67	4.20	2.60	2.78	5.02
752	4.34	4.93	3.34	3.14	5.56
842	4.90	5.45	4.01	3.83	5.89
932	5.40	5.92	4.54	4.32	6.39
1112	6.31	6.67	5.33	5.50	6.99
1292	70.6	7.17	6.11	6.12	7.45
1472	7.48	7.56	6.64	6.66	7.87
1652	7.70	8.12	7.10	7.10	8.17
1832	—	—	7.45	—	—
Mechanical properties (as mill annealed)					
Tensile strength, ksi	65	65	75	82	80
Yield strength, ksi	40	40	42	40	40
Elongation in 2 inches, %	35	35	30	30	30
Hardness, Rockwell B	70	70	76	76	80
Elastic modulus, ksi × 10^3	20.5	20.5	21.0	21.0	23

[*] Also available at carbon 0.01% (max).
[†] Unannealed.
[‡] Fully aged.

Thermal expansion properties below 77°F of several alloys are given in Table 4.12. For the effect of elevated temperature on the physical properties of a nickel-iron alloy, Fig. 4.19 provides nominal data observed on 42 Ni, balance Fe.

TABLE 4.12 Coefficients of Thermal Expansion of Nickel-Iron Alloys Annealed at or below Room Temperature

	In/in × 10^{-6}/°F		
Temperature, °F	36 Ni, bal. Fe	42 Ni, bal. Fe	49 Ni, bal. Fe
0–77	0.8	3.1	5.1
– 100 –	0.9	3.4	5.2
– 200 –	0.9	3.5	5.1
– 300 –	1.0	3.5	4.8

4.2.10.2 Stainless steels (ferritic and austenitic). Thermal expansion properties of ferritic stainless steels are presented in Table 4.13, and these properties are greater than those of the nickel-iron family, having 49 percent nickel and less. Lower cost and other specific properties favor these alloys in some applications. Exposure to high elevated temperatures can alter the expansion properties through metallurgical phase changes. The expansion properties are altered when austenite is formed in the alloy and the deletion of the austenitic phase is sluggish on cooling after being formed. As the chromium content increases, the ferrite is more stable with increasing temperature; titanium increases the ferrite stability.

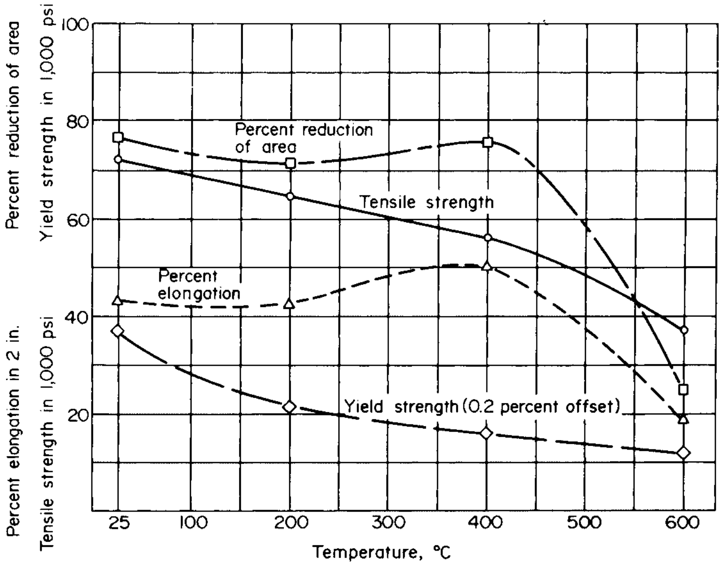

Figure 4.19 Physical properties of 42 Ni, bal. Fe (annealed).

TABLE 4.13 Thermal Expansion and Physical Properties of Ferritic Stainless Steels, Type 400 Series

Property	Type 410, Type 416*	Type 430, Type 430 F*	Type 430 Ti	Type 446	29% Cr alloy
Chromium content, %	13.0	17.5	18.2	24.0	28.0
Specific gravity	7.7	7.7	7.7	7.7	7.60
Density, lb/in^3	0.28	0.28	0.28	0.28	0.27
Thermal conductivity at 32–212°F, Btu/(hr)(ft^2)(°F/ft)	14.4	15.1	15.1	12.1	13.2
Electrical resistivity, Ω/cir mil-ft	343	361	361	385	385
Specific heat, Btu/(lb)(°F)	0.11	0.11	0.11	0.12	0.14
Structure	martensitic	ferritic	ferritic	ferritic	ferritic
CTE, in/(in)(°F), annealed					
At 77–212°F	5.5	5.6	5.10	5.2	5.20
392	6.1	5.8	5.50	5.6	5.60
572	6.3	6.1	5.80	6.0	5.86
752	6.5	6.3	6.05	6.0	5.98
932	6.7	6.5	6.30	6.2	6.19
1112	6.8	6.6	6.50	6.3	6.25
1292	7.0	6.8	—	6.4	6.46
1472	—	7.0	—	6.5	6.48
1652	—	7.1	—	7.0	7.09
Mechanical properties (as annealed)					
Tensile strength, ksi	70	75	75	85	85
Yield strength, ksi	45	45	45	55	55
Elongation in 2 inches, %	25	30	30	25	25
Hardness, Rockwell B	80	75	75	80	85
Elastic modulus, ksi × 10^3	29	29	29	30	30

*S = 0.30 for better machinability.

Properties of several austenitic stainless steels are given in Table 4.14. Alloys in this series have very high coefficients of expansions; the values are slightly lower than the 22 Ni, 3 Cr, balance Fe alloy given in Table 4.11.

4.2.10.3 Glass-to-metal sealing alloys. A glass-to-metal seal is a vacuum-tight bond between a glass and a metal. The seal, depending on the design, is used to conduct a form of electricity into a chamber or to provide a structural advantage such as a transparent window or a support. To achieve a vacuum-tight and strong glass-to-metal seal, the glass and metal must have practically identically thermal expansion characteristics below the setting point of the glass so as to have minimum stress at the glass-to-metal interface and within

TABLE 4.14 Thermal Expansion and Physical Properties of Austenitic Stainless Steels, Type 300 Series

Property	Type 301	Types 303, 302, 304	Type 316	Type 347	Type 310	Type 330
Typical chromium content, %	17.0	18.0	17.0	18.0	25.0	18.0
Typical nickel content, %	7.0	10.0	12.0	11.0	21.0	35.0
Specific gravity	8.0	8.0	8.0	8.0	8.0	8.0
Density, lb/in^3	0.29	0.29	0.29	0.29	0.29	0.29
Thermal conductivity at 32–212°F, Btu/(hr)(ft^2)(°F/ft)	9.4	9.4	9.4	9.3	8.0	10.8
Electrical resistivity, Ω/cir mil-ft	435	433	445	438	469	600
Specific heat, Btu/(lb)(°F)	0.12	0.12	0.12	0.12	0.12	0.11
CTE, in/in × 10^{-6}/°F, annealed						
At –300 to +70°F	7.6	7.4	7.1	7.5	7.0	5.8
–200	7.8	7.7	7.4	8.1	7.5	6.5
–100	8.2	8.2	7.8	8.5	7.8	7.2
0	8.7	8.7	8.2	8.7	8.0	7.6
+70 to +200	9.2	8.8	8.9	9.0	8.4	8.1
300	9.4	9.0	9.2	9.2	8.6	8.3
400	9.5	9.2	9.3	9.4	8.8	8.5
500	9.6	9.4	9.4	9.5	8.9	8.7
600	9.7	9.5	9.6	9.7	9.0	8.9
700	9.8	9.7	9.7	9.8	9.2	9.0
800	9.9	9.8	9.8	9.9	9.3	9.1
900	10.0	9.9	9.9	10.0	9.4	9.3
1000	10.1	10.0	10.0	10.1	9.5	9.4
Mechanical properties (as annealed)						
Tensile strength, ksi	110	85	84	95	95	70
Yield strength, ksi	40	42	42	40	4	35
Elongation in 2 inches, %	60	55	50	45	45	30
Hardness, Rockwell B	85	80	80	85	85	85
Elastic modulus, ksi × 10^3	28	28	29	28	29	

the glass.[13–15] Metal parts, fabricated to the final shape employed in making the glass-to-metal seal, must have a thoroughly clean surface. The strongest seals are achieved when a tight metal oxide film is produced on the surface of the metal before the glass comes in contact with the sealing surface. This oxide can be generated by a prior thermal treatment or by heating the metal for sealing. The oxide roughens the surface of the metal and is soluble in the molten glass, thus increasing the area of contact. Small bubbles within the glass-to-metal interface are undesirable and are an indication of a weak bond. The bubbles can be eliminated by a prior treatment of the metal in a wet hydrogen atmosphere to clean and/or decarburize the metal surface. After the sealing operation, an annealing treatment should be employed so that the nonequilibrium stresses within the glass are removed.

Chromium-iron alloys. Chromium-irons such as Type 430; Type 430Ti; Type 446; and 28 Cr, balance Fe are employed. Selection depends on the sealing temperature employed. Type 430 is not recommended for temperatures above 1700°F so as to avoid the formation of austenite in the alloy. The presence of austenite increases the degree of contraction on cooling and can result in cracked or overstressed seals. Type 446 will withstand higher sealing temperatures up to 2000°F, depending on chromium content and other elements in the analysis.[16] Type 430 Ti and 28 Cr, balance Fe have the most stable ferrite of the commercial grades. To obtain the strongest glass-to-metal seal, the parts should be heated in a wet hydrogen atmosphere to produce a greenish black oxide that is very tightly adherent to the base metal. Heating in air or a gas-firing flame for sealing to produce a sealing oxide is being used successfully.

Nickel-iron alloys.[17] Most common grades contain the nominal nickel contents of 42, 46, 48, and 50.5 percent. Most grades must be degassed in wet hydrogen before sealing. A typical treatment is to heat to 1750°F in wet hydrogen for 30 min. Preoxidizing treatments or flame oxidizing can be used. The 42 percent nickel alloy is generally used for ring (housekeeper type) seals with hard glasses whereby a feathered edge is inserted in the glass. This thin wall absorbs the expansion difference between the metal and the glass. The other alloys can be used for various internal, external, butt, and other types of seals, depending on the match with the various types of soft glasses-having a coefficient greater than 2.8×10^{-6} in/(in)(°F).

Gas-free types are available in several of these grades, and these have low carbon contents or other additives.

42 Ni, 6 Cr, balance Fe.[18] Because of the chromium content in this alloy, a very tight greenish black oxide can be formed on the alloy in a wet hydrogen atmosphere. Treatments to form the oxide range from 1950 to 2350°F, with varying time until the thin tight oxide is formed. This varies from facility to facility, each of which must be evaluated. To remove the oxide after cleaning, refer to the discussion of chromium-iron alloys.

28 Ni, 17 Co, balance Fe.[19] This alloy is most commonly used to make glass-to-metal seals with the hard glasses of the Pyrex® type; hard glasses are defined as having a coefficient of expansion less than 2.8×10^{6} in/(in) (°F) up to 572°F. Because of the high sealing temperature, these alloys should be degassed as prescribed previously to produce good glass-to-metal seals. Preoxidizing or flame oxidizing can be employed before making the seal. If glass-to-metal seals are to be exposed to temperatures below –100°F, the alloy should be checked for phase transformation, which alters the expansion properties and could result in cracked or overstressed seals.

Mild or low-carbon steel. AISI 1010 can be used to make certain types of internal and external glass-to-metal seals. The expansion coefficient of expansion over the range of 77 to 572°F is 6.95×10^{6} in/(in)(°F). This alloy is sometimes plated before being subjected to a degassification treatment. Preoxidizing or flame oxidizing can be employed.

4.2.11 General comments on metal fabrication

4.2.11.1 Deep drawing. The best ductility is exhibited by the nickel-iron alloys: 42 Ni, 6 Cr, balance Fe and the 28 Ni, 17 Co, balance Fe alloy. First draws of as much as 50 percent are achievable, with second redraws up to 25 percent. Less ductility is exhibited by the 28 Cr, balance Fe alloy, with which first draws should not exceed 20 percent.

4.2.11.2 Welding. With the exception of the chromium-irons, all grades can be welded by all techniques with precautions. Chromium-iron alloys can be spot-welded with precautions.

4.2.11.3 Photochemical machining. All grades can be photochemically machined with precautions. The vendor should be advised if this processing will be employed so as to achieve best performance.

4.2.11.4 Ceramic-to-metal sealing alloys. To obtain the best ceramic-to-metal seal, both ceramic and metal must have matching expansion characteristics. Generally, the bond is made with a brazing alloy. Precautions must be exercised during this treatment, because overheating may tend to cause excessive penetration of the brazing alloy into the metal. Intergranular penetration of the brazing alloy can be retarded by copper, silver, or nickel plating the metal in the area to be sealed.

4.2.11.5 Constant modulus of elasticity alloys. The iron-nickel-chromium-titanium alloy is age hardenable and exhibits a constant modulus in the temperature range of –50 to +150°F. The alloy is available in the forms of wire, rod, strip, round tube, and forgings. To achieve the lowest thermoelastic coefficient in the range of -10 to $+10 \times 10^6$/°F, the parts must be thermally aged as a final heat treatment. Through utilization of an annealing solution treatment of approximately 1850°F and rapid quench and/or percentages of cold reduction (if possible on the cross section), variations in high tensile strength, hardness, and near-zero thermoelastic coefficients are obtainable. Slight differences in chemical analysis between melts result in minor variations; hence, for very precise applications, adjustments in heat treatments are predictable through information available from the producer.

4.2.12 Electrical-resistance alloys and electrical resistivity properties of some ferrous alloys

Electrical-resistance alloys are generally used to produce heat or to control electric current. In some cases, the electrical resistance or resistivity is a minor property for the selection of a given alloy. Standard procedures have been established to determine these electrical characteristics. Table 4.15 provides the electrical resistivity of some alloys and the effect of temperature on this property. The electrical resistivity of most alloys increases with increasing temperature.

Ferrous alloys and pure metals are not recommended for precision resistors because of their high-temperature coefficients. Several nonferrous alloy series are available for manufacturing wire-wound resistors to meet a variety of requirements.[9]

4.2.13 Aluminum and aluminum alloys

4.2.13.1 General properties. Aluminum and its alloys possess properties that find wide use in the electronics industry. Favorable physical properties, good strength-to-weight properties, good corrosion resistance, and low density, combined with economy in material cost and fabrication cost, make this alloy family a basic construction material for electronic assemblies.

Electrical properties of aluminum. Electrical conductivity of the higher-purity grades is 62 percent of that of pure copper on a volume basis and exceeds copper by approximately twice on a per-pound basis. Alloying to increase strength results in lower conductivity, but fairly strong alloys are available that still exceed the conductivity of copper on a weight basis.

Thermal conductivity of aluminum. The high thermal conductivity of aluminum is an advantage in dissipating heat, which is often a requirement in electrical apparatus.

Density of aluminum. The light weight of aluminum can often result in a reduction in weight as compared to materials that are stronger than aluminum on a volume basis. The fact that aluminum covers more area per pound when substituted gage for gage for copper alloys, nickel alloys, or steel, results in more favorable material costs, because the same weight of aluminum will cover a larger area than will the heavier alloys.

Strength-weight of aluminum. Although aluminum alloys cannot match high-strength steels, beryllium-copper, high-strength titanium alloys, or some nickel alloys in strength per unit area, its low density makes it competitive on a strength-weight basis at room temperature and at slightly elevated temperatures. At low temperatures, even in the cryogenic range, aluminum alloys retain good ductility and thus have found use in low-temperature pressure vessels.

Corrosion of aluminum. Corrosion resistance in aluminum is good to the extent that many applications require no protection. Corrosion resistance varies according to the alloying elements used, with the higher-purity alloys generally having best corrosion resistance. In severe environments, protection is needed, especially for the higher-strength alloys. This protection can be provided by anodizing or by conversion coating, either alone or in combination

TABLE 4.15 Electrical Resistivities of Some Alloys and Factors for Calculating Values at Elevated Temperatures

Composition	Resistivity at 68°F, Ω/cir mil-ft	Calculation factors at:										
		200°F	400°F	600°F	800°F	1000°F	1200°F	1400°F	1600°F	1800°F	2000°F	2100°F
36 Ni, bal. Fe	484	1.09	1.185	1.25	1.3	1.35	1.386	1.42	1.45	1.48		
NiSpan C	625	1.03	1.06	1.11	1.16	1.23						
80 Ni, 20 Cr, 1.5 Si	650	1.016	1.037	1.054	1.066	1.070	1.064	1.064	1.066	1.072	1.078	1.084
60 Ni, 15 Cr, bal. Fe	675	1.019	1.044	1.070	1.092	1.108	1.112	1.118	1.130	1.145		
35 Ni, 15 Cr, bal. Fe	600	1.029	1.067	1.105	1.137	1.167	1.187	1.206	1.223			
23 Cr, 6.2 Al, 1.9 Co, bal. Fe	836	1.002	1.005	1.009	1.014	1.020	1.024	1.028	1.037	1.045		
22.6 Cr, 4.5 Al, 2 Co, bal. Fe	812	1.002	1.005	1.009	1.014	1.020	1.024	1.028	1.037	1.045	1.050	1.055
16 Cr, 5 Al, bal. Fe	800	1.007	1.018	1.032	1.053	1.084	1.116	1.137			1.055	1.053
Types 302 and 304	435	1.08	1.18	1.28	1.37	1.44	1.50	1.65	1.75	1.82		
Type 316	445	1.07	1.17	1.26	1.34	1.41	1.59					
Type 321	435	1.10	1.25	1.36	1.45	1.55	1.62	1.68				
Type 347	440	1.09	1.20	1.25	1.35	1.46	1.52	1.58	1.64			
Type 309	470	1.07	1.17	1.26	1.35	1.42	1.48	1.53	1.58	1.62		
13 Cr, 4 Al	672	1.005	1.02	1.04	1.06	1.09	1.14	1.18				
Type 410	345	1.11	1.26	1.43	1.58	1.73	1.90	2.02				
Type 430	360	1.11	1.27	1.42	1.58	1.72	1.86	1.96				
Type 446	405	1.1	1.24	1.37	1.50	1.60	1.70	1.76				

with painting. Because aluminum is galvanically dissimilar to most common structural metals, it is necessary to pay special attention to applications in which it comes into contact with other metals.

Availability. Aluminum alloys are available in about every form, including sheet, plate, foil, pipe, tubing, forgings, and castings, as well as all types of extrusions and rolled shapes. Not all alloys are available in all shapes. This is especially true of castings, which are furnished in an entirely different group of compositions than are wrought alloys.

Fabrication of aluminum. The fabrication of aluminum can be carried out by all common means. Machining is very good, but the softer alloys and tempers tend to be gummy. Formability is excellent at room temperature.

Joining of aluminum. Joining can be accomplished by mechanical means such as bolts, screws, and rivets as well as by the metallurgical processes of welding, brazing, and soldering. However, precautions must be taken in selecting alloys for the metallurgical processes. Certain alloys are difficult to weld. The brazing alloys melt at a temperature that exceeds the melting point of certain of the commonly used alloys, thus making selection of materials to be brazed subject to careful consideration. Solders are available for aluminum, but corrosion by galvanic action between the aluminum and solder alloys may be a problem where moisture is present. Fluxes for brazing and soldering are highly active and will cause corrosion if left on the parts, thus making post-joining cleaning of paramount importance. Fluxless brazing has been done in vacuum furnaces and is currently under development. Successful fluxless soldering has been accomplished with ultrasonic devices. These processes eliminate the flux corrosion hazard.

4.2.13.2 Aluminum alloy groups.

Table 4.16 shows the four-digit system for designating alloy groups on the basis of composition as devised by the Aluminum Association.

TABLE 4.16 Wrought Designation System for Aluminum Alloys

Series number	Primary alloying element	Relative corrosion resistance	Relative strength	Heat treatment
1xxx	none	excellent	fair	not heat treatable
2xxx	copper	fair	excellent	heat treatable
3xxx	manganese	good	fair	not heat treatable
4xxx	silicon	—	—	not heat treatable
5xxx	magnesium	good	good	not heat treatable
6xxx	magnesium and silicon	good	good	heat treatable
7xxx	zinc	fair	excellent	heat treatable

4.2.13.3 Aluminum alloy temper designations. For aluminum, there are two types of designations. The -H designations represent cold-worked conditions and are used for non-heat-treatable alloys. The -T designations are used for heat-treatable alloys that are primarily strengthened by heat treatment. It will be noted that the -T designations also include conditions that result from cold-working combined with heat treatment.

4.2.13.4 Mechanical properties—wrought aluminum alloys. In general, tensile values are above the specified minimum except for the annealed (–O Temper) values, which are below a specified maximum. These values are the most probable figures to be found when testing a large number of specimens.

The properties will also depend to a significant extent on the form in which the alloy is used. Thin sheet will generally have higher strength than thick plate of the same composition and heat treatment. Direction of loading will also influence the properties. In critical applications where safety margins are low, consultation with the producer for guaranteed properties is desirable. Standard specifications are available for most aluminum alloys in most forms. These specifications have minimum and/or maximum property limits that take into account section size, method of manufacture, and other process variables. Producers are able to guarantee compliance with these specifications.

4.2.13.5 Effect of temperature on mechanical properties of aluminum alloys. Elevated temperatures have an adverse effect on the mechanical properties of aluminum alloys. Other properties, such as fatigue strength and shear strength, will also show similar changes. It is obvious that moderately elevated temperatures over time can have appreciable effects on the mechanical properties of aluminum alloys. Note that alloys that are strongest at room temperature are not necessarily the strongest at elevated temperatures. Additional data is available through the Aluminum Association, Washington, DC.

4.2.13.6 Physical properties of aluminum. Table 4.17 shows a compilation of electrical properties at room temperature. These values will also change with change in temperature.

4.2.13.7 Cast aluminum alloys. Aluminum alloys can be cast by all available casting methods, including sand, die, investment, permanent mold, and plaster mold. Casting compositions are specifically designed for cast forms and differ significantly from those of the alloys used for wrought forms such as sheet, box, extrusions, and forgings. As a result, some of the highest electric and thermal conductivity values found in wrought alloys cannot be found in casting alloys. However, aluminum castings exhibit the favorable corrosion resistance and strength-to-weight ratio found in wrought alloys.

TABLE 4.17 Typical Thermal and Electrical Properties of Aluminum Alloys[1]

		Thermal conductivity @ 25°C (77°F)		Electrical conductivity @ 20°C (68°F), % of Intl. Annealed Copper Standard		Electrical resistivity @ 20°C (68°F)	
Alloy	Temper	Cgs units*	English units†	Equal volume	Equal weight	µΩ/cm	Ω/cir mil-ft
EC‡	All	0.56	1625	62	204	2.8	17
1060	0	0.56	1625	62	204	2.8	17
	H18	0.53	1540	61	201	2.8	17
1100	0	0.53	1540	59	194	2.9	17
	H18	0.52	1510	57	187	3.0	18
2011	T3	0.36	1040	39	123	4.4	27
	T8	0.41	1190	45	142	3.8	23
2014	0	0.46	1340	50	159	3.4	21
	T4	0.32	930	34	108	5.1	31
	T6	0.37	1070	40	127	4.3	26
2017	0	0.46	1340	50	159	3.4	21
	T4	0.32	930	34	108	5.1	31
2018	T61	0.37	1070	40	127	4.3	26
2024	0	0.46	1340	50	160	3.4	21
	T3, T4, T36	0.29	840	30	96	5.7	35
	T6, T81, T86	0.36	1040	38	122	4.5	27
2025	T6	0.37	1070	40	130	4.3	26
2117	T4	0.37	1070	40	130	4.3	26
2218	T72	0.37	1070	40	126	4.3	26
2219	0	0.41	1190	44	138	3.9	24
	T31, T37	0.27	780	28	88	6.2	37
	T62, T81, T87	0.30	870	30	94	5.7	35
3003	0	0.46	1340	50	163	3.4	21
	H12	0.39	1130	42	137	4.1	25
	H14	0.38	1100	41	134	4.2	25
	H18	0.37	1070	40	130	4.3	26
3004	All	0.39	1130	42	137	4.1	25
4032	0	0.37	1070	40	132	4.3	26
	T6	0.33	960	35	116	4.9	30
4043	0	0.39	1130	42	137	4.1	25
5005	All	0.48	1390	52	172	3.3	20
5050	All	0.46	1340	50	165	3.4	21
5052	All	0.33	960	35	116	4.9	30
5056	0	0.28	810	29	98	5.9	36
	H38	0.26	750	27	91	6.4	38
5083	All	0.28	810	29	98	5.9	36
5086	All	0.30	870	31	104	5.5	34
5154	All	0.30	870	32	107	5.3	32
5252	All	0.33	960	35	116	4.9	30

TABLE 4.17 Typical Thermal and Electrical Properties of Aluminum Alloys[1] (Continued)

Alloy	Temper	Thermal conductivity @ 25°C (77°F)		Electrical conductivity @ 20°C (68°F), % of Intl. Annealed Copper Standard		Electrical resistivity @ 20°C (68°F)	
		Cgs units[*]	English units[†]	Equal volume	Equal weight	μΩ/cm	Ω/cir mil-ft
5454	0	0.32	930	34	113	5.1	31
	H38	0.32	930	34	113	5.1	31
5456	0	0.28	810	29	98	5.9	36
5557	All	0.45	1310	49	159	3.5	21
6053	0	0.41	1190	45	148	3.8	23
	T4	0.37	1070	40	132	4.3	26
	T6	0.39	1130	42	139	4.1	25
6061	0	0.43	1250	47	155	3.7	22
	T4	0.37	1070	40	132	4.3	26
	T6	0.40	1160	43	142	4.0	24
6063	0	0.52	1510	58	191	3.0	18
	T1[§]	0.46	1340	50	165	3.4	21
	T5	0.50	1450	55	181	3.1	19
	T6, T83	0.48	1390	53	175	3.3	20
6066	0	0.37	1070	40	132	4.3	26
	T6	0.35	1010	37	122	4.7	28
6070	T6	0.41	1190	44	145	3.9	24
6101	T6	0.52	1510	57	188	3.0	18
	T61	0.53	1540	59	194	2.9	18
	T63[¶]	0.52	1510	58	191	3.0	18
	T64	0.54	1570	60	198	2.9	17
	T65	0.52	1510	58	191	3.0	18
6151	0	0.49	1420	54	178	3.2	19
	T4	0.39	1130	42	138	4.1	25
	T6	0.41	1190	45	148	3.8	23
6262	T9	0.41	1190	44	145	3.9	24
6463	T1[§]	0.46	1340	50	165	3.4	21
	T5	0.50	1450	55	181	3.1	19
	T6	0.48	1390	53	175	3.3	20
7001	T6	0.29	840	31	104	5.5	34
7039	T61	—	—	35	116	4.9	30
7072	0	0.53	1540	59	193	2.9	18
7075	T6	0.31	900	33	105	5.2	31
7079	T6	0.30	870	32	104	5.4	32
7178	T6	0.30	870	31	98	5.6	33

[*] Cgs units = cal/(sec)(cm^2)(°C/cm).
[†] English units = Btu/(hr)(ft^2)(°F/in).
[‡] Electrical conductor grade, 99.45% minimum aluminum.
[§] Formerly designated T42.
[¶] Formerly T62.

In the design of castings, it is important to work with the foundry as early in the process as possible, because there is room for wide variation in the strength and quality of castings, depending on the factors mentioned above. The following major questions should be jointly answered by the purchaser and vendor:

1. How are mechanical properties to be determined? Are they to be determined on separately cast test bars or on test bars from the casting itself? Many specification properties are based on separately cast test bars, and the properties of the casting can be considerably lower than those specified. On the other hand, foundries will agree to guaranteeing properties of the actual casting in some instances.
2. What level of defects is to be allowed, and what means of inspection is to be used?

A procedure covering means of specifying and controlling these factors is outlined in AMS-STD-2175.

Selection of alloy. Casting alloy selection is not so straightforward as wrought alloy selection. The casting selection is complicated by the foundry characteristics of the alloy and by the foundry practice used in production. It may often be the case that a sound, inherently low-strength material will exceed the strength of a high-strength material of poor quality.

4.2.13.8 Recommended aluminum casting alloys. In electronics packaging, certain grades of castings may be recommended for specific purposes.

General-purpose aluminum alloy. Alloys 356 and A356 are the most widely used alloys in production. They have good foundry characteristics and very good mechanical properties. They are available in sand, permanent-mold, investment, and plaster-mold castings.

Brazable compositions. Alloys A612 and C612 are most commonly used for parts that must be brazed, because their melting points are high enough to withstand brazing temperatures.

Low thermal expansion. The high-silicon-content (18 to 20 percent silicon) alloys have thermal expansion rates close to that of alloy steel. These alloys are difficult to cast and must be carefully poured with special procedures.

High-strength. Some aluminum alloys have approached the strength of the higher-strength wrought aluminum alloys. Alloy 220 gives a tensile strength above 40,000 psi with good ductility, but it is difficult to cast.

The importance of close cooperation with foundries in early stages of casting design cannot be emphasized too strongly. Agreement should be reached on tolerance, quality standards, and strengths.

4.2.14 Beryllium and beryllium alloys

Beryllium has a combination of physical and mechanical properties that make it a natural material for use in electronic packaging as a structural material and as a material for thermal and electrical functions. The high cost of beryllium metal, combined with difficulties in joining and forming it, have made beryllium structures very expensive. In addition, the lack of ductility of the metal has precluded its use in many structural applications. A combination of beryllium and aluminum called AlBeMet* can overcome, to some extent, the forming, joining, and ductility problems while retaining many of the desirable beryllium characteristics. Even with the addition of aluminum, material costs remain high. Despite its drawbacks, there are applications for which the high stiffness-to-weight and strength-to-weight ratios of beryllium and AlBeMet make their use cost effective in terms of weight reduction. Mirror blanks, gyro parts, airframe and missile body stiffeners, and control surfaces on airplane are examples of structural uses of these materials. The high thermal conductivity of pure beryllium, along with its high heat capacity, makes it a natural lightweight heat sink.

4.2.14.1 Availability. As mentioned above, beryllium is available in two basic compositions, these being essentially pure beryllium with various beryllium oxide contents and the material AlBeMet, which is a combination of beryllium and aluminum. The production methods for both of these alloys are advancing, with the result that products with improved properties are being developed, as well as capability for producing the materials in new forms. Aluminum-beryllium alloys are available in cast form. Close liaison with suppliers during the early stages of planning is recommended so that the most suitable product available is used. Aluminum-beryllium alloys are covered by three commercial specifications: AMS 7911, Aluminum-Beryllium Alloy, Hot-isostatic Pressed (HIP); ASE-AMS, 7912, Aluminum-Beryllium Alloy, Extrusions; and SAE-AMS 7913-97, Aluminum-Beryllium Alloy, Sheet and Plate 38AL-62BE.

A large amount of beryllium metal is produced in the form of hot-pressed block. This product is produced by first casting the metal into an ingot, which is then reduced to a powder stage by mechanical means. The powder is then compacted into a block by heat and pressure. Many beryllium parts are produced by machining from the hot-pressed block.

Extruded rod, tube, and bar produced by extruding hot-press block or billets are also available. Sheet that has been rolled from hot-pressed block is also procurable. In addition, sheet is being rolled directly from the cast ingot in some cases, and forged blocks are available.

The working done by extrusion and rolling results in material of improved properties (both strength and ductility) over the hot-pressed block. Beryllium is susceptible to developing directionality in properties because of working. Often, good ductility is present in one direction while being very poor in other directions. One method used in sheet production is to cross-roll. A designer should be aware of these directional properties and discuss specific requirements with the supplier.

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* Registered trademark of Brush Wellman.

Aluminum-beryllium alloys are typically produced by extrusion in the form of bar and shapes. Dies for some simple structural shapes are easily fabricated. Consultation with the supplier on shape and size availability is recommended. Sheet and plate are produced by cross-rolling extruded rectangular bars.

4.2.14.2 Chemical composition. Beryllium is produced with controlled beryllium oxide content. It is typically supplied either as a commercially pure product or alloyed with aluminum. The major aluminum-beryllium alloy composition is the 62 percent beryllium, 38 percent aluminum composition.

4.2.14.3 Physical properties. Table 4.18 covers some physical properties of beryllium. Poisson's ratio is extremely low as compared to that of other structural metals. This value should be considered as provisional, and the supplier should be consulted as to actual values for available material, because there seems to be some conflict in data.

TABLE 4.18 Some Physical Properties of Beryllium*

Atomic diameter, A°	2.221	Latent heat of fusion, cal/g	250–275
Atomic number	4	Latent heat of vaporization	5390
Atomic weight	9.02	Magnetic susceptibility, gauss/oersted cgs	0.79
Density, g/cc	1.85	Thermal neutron absorption cross section, barn/atom	0.0090 ± 0.0005
Density, psi	0.055	Beryllium atoms per cm^3	1.24×10^{23}
Electrical conductivity, % IACS	38–40	Thermal-neutron scattering cross section, barn/atom	7.0
Electrode potential, V	–1.69	Slowing-down length, cm (fission energy to thermal energy)	9.9
Electrochemical equivalent, mg/coul.	0.04674	Velocity of sound:	
Phoelectric work function, eV	3.92	ft/sec	41,300
Hall coefficient, cgs electromagnetic units	0.0024 ± 0.001	m/sec	12,600
Mass susceptibility:		Entropy, $S_{298.1}$, cal/(mole)(kelvins):	
–180°C	–0.72 cgs units	Solid	2.28 ± 0.02
+20°C	–1.00 cgs units	Liquid	32.56 ± 0.01
+300°C	–1.20 cgs units	Reflectivity (white light)	50/55
Melting point, °C	1285	Photoelectric work function, eV	3.92(9)
Melting point, °F	2345	Poisson's ratio	0.25 ± 0.005
Boiling point, °C	2970		
Boiling point, °F	5378		

*SOURCE: Kawecki Berylco Industries, Technical Bulletin 304 03 PDI.

4.2.14.4 Corrosion resistance and finishing. Beryllium is susceptible to corrosion by chlorides. This factor alone makes it necessary to protect the metal from corrosion, because most equipment will be subjected to some chloride environment during service. Because field-performance data are practically nonexistent, it is recommended that testing be carried out under simulated service conditions.

Aluminum-beryllium alloys possesses some of the favorable corrosion resistance of aluminum. Because the material is essentially a mixture of beryllium and aluminum, there exists a possibility of some galvanic corrosion effects. Service data on corrosion are not readily available, given that aluminum-beryllium alloys are typically coated to prevent corrosion or are used in space applications. As with beryllium, corrosion testing under simulated service testing is recommended, with due caution to safety with regard to the potential hazards of corrosion products.

4.2.14.5 Protective coatings for beryllium and aluminum-beryllium alloys. Both conversion coatings and anodic coatings are available for AlBeMet and beryllium. These coatings offer added corrosion resistance over that of the bare metals. Proprietary treatments are available from the metal producers.

Electroplating of beryllium is a production procedure. The common electroplated coatings may be applied. Typically, aluminum-beryllium alloys accept platings by standard techniques used for aluminum.

In general, it appears that both beryllium and aluminum-beryllium alloys—with suitable finish selected from conversion coatings, anodizing, or electroplating—can meet the corrosion-resistance requirements for most electronic applications.

4.2.15 Fabrication of beryllium alloys

4.2.15.1 Toxicity. Breathing of beryllium oxide dust particles generated from machining beryllium is a health hazard, so any operation that could create fine particles must be done under conditions that prevent any possible inhalation of these particles. The same precautions as taken with beryllium must be taken with aluminum-beryllium alloys. All machining operations must be done under conditions in which the particles created are collected at the tool and isolated in a container to preclude their discharge into the atmosphere. Heating operations such as welding and brazing must be similarly controlled. Before processing beryllium or aluminum-beryllium alloys, consultation with plant safety engineer, local government medical authorities, vendor safety department, and other cognizant safety or health officials is mandatory.

4.2.15.2 Machining. Beryllium can be machined by conventional machining methods. Tool wear will be high because of the abrasive nature of the material.

Most cutting-type operations leave a surface damage in the form of microcracks. These small cracks will act as failure initiation points. Removal of the surface layer by etching is required if structural integrity is to be maintained.

Aluminum-beryllium alloys can be machined by conventional techniques.

4.2.15.3 Forming. The brittle nature of beryllium makes forming a problem. Most forming is done at elevated temperatures.

AlBeMet has greatly improved formability over beryllium. Processes such as semisolid metalworking (SSM) have been used to form aluminum-beryllium alloys to near net shape, reducing raw material costs at the expense of additional tooling cost.

4.2.15.4 Joining. Mechanical fastening of beryllium must be done with care, because the drilling of holes will cause microcracks. Riveting operations may cause cracking of the structure.

AlBeMet may be joined satisfactorily by riveting, because its increased ductility will absorb impact, and surface damage from machining is not a major problem.

Welding of beryllium results in brittle welds that so far have not been considered satisfactory. AlBeMet appears to be weldable with either AlBeMet filler rod or with aluminum alloy filler rod.

Brazing of beryllium is practicable using either conventional aluminum brazing alloys or silver brazing alloys. AlBeMet may be brazed with aluminum brazing alloys.

4.2.15.5 Cost. Toxicity and high raw material costs are the two major issues to be considered when specifying beryllium. When performance standards such as low density, high stiffness, good thermal conductivity, and low thermal expansion are required, beryllium and aluminum-beryllium alloys should be considered. It is obvious that these materials must offer major design advantages to be cost effective in comparison with more conventional materials.

4.2.16 Copper and copper alloys

4.2.16.1 General characteristics. Copper and copper alloys to a great extent still dominate electrical-conductor applications in electronic equipment, even though aluminum and its alloys can show weight reduction and lower material cost. Among the characteristics that account for use of copper and its alloys are the following:

1. Pure copper has the highest electrical conductivity of any metal except silver when considered on a volume basis. As a result, copper electrical conductors require the lowest space for a given conductivity.
2. Forming characteristics of copper are exceptionally good and make economics of manufacture favorable.
3. Solderability of copper is good although, for most electric soldering, a solderable finish is required.
4. The application of finishes by electroplating is easy and reliable, as is the application of hot-dipped coatings.
5. The basic corrosion resistance of copper is good, and, again, finishes are easily and economically applied.

6. The availability of copper forms includes all sizes and shapes, including extremely fine wire, thin strip, and castings, as well as sheet, plate, bar, forgings, and extrusions.
7. Copper is suitable for many plant forming operations and lends itself to all machining operations. Such methods as electroforming and chemical milling are especially useful in shaping copper alloys.
8. The basic costs of copper and its alloys are still reasonable.
9. Thermal conductivity is high, offering a good means of transferring heat from components to a heat sink.

The above characteristics apply in general to copper and copper alloys. Note that alloying can drastically affect these properties. Some of the copper alloys have an electrical conductivity as low as 5.5 percent. Examine carefully all properties when selecting an alloy. Trade-offs sometimes will be required between such properties as strength and electrical conductivity. ASTM B152/B152M is a commercial specification that is commonly used for copper and copper alloy sheet strip and plate.

4.2.16.2 High-electrical-conductivity alloys (UNS C10xxx and C11xxx). Hundreds of copper alloy compositions are available. These range from high-purity copper to multiple alloys. Compositions are Copper Development Association/UNS designations. Alloys are distinguished by several characteristics.

The tough-pitch grades are probably the most widely used for electrical conductors. In the annealed condition, their electrical conductivities are approximately 100 percent International Annealed Copper Standard (IACS). The major drawback to these compositions, compared to the other high-conductivity coppers, is that they are subject to embrittlement by hydrogen at elevated temperatures of 700°F and above. This is because of the presence of oxygen in the metal, which will combine with hydrogen, resulting in internal cracking of the metal. Because most brazing operations involve hydrogen, either in the products of combustion of the heating gases or in furnace atmospheres, tough-pitch copper is not usually suitable where brazing is to be used in joining.

This problem can be overcome by use of copper with low oxygen content. Phosphorous deoxidized copper is one approach to solving this deficiency. The use of phosphorous as a deoxidizer results in a slight reduction of electrical conductivity and somewhat reduced formability.

Oxygen-free copper, which is produced without the use of metal deoxidizers, results in a product that is free from susceptibility to hydrogen embrittlement, retains 100 percent or better electrical conductivity, and has a formability equivalent to that of tough-pitch copper.

4.2.16.3 Silver-bearing coppers (UNS C12500 to C13000). High-conductivity coppers are also available with small amounts of silver present in the composition. These alloys retain the approximately 100 percent electrical conductivity, with two additional advantages of improved creep resistance and resistance to softening at elevated temperatures. The latter advantage is useful if work-hardened material must be subjected to elevated temperatures during processing and it is desired to retain the work-hardened condition. The silver-bearing alloys will resist annealing at temperatures as high as 650°F, a temperature that will substantially anneal the pure coppers.

Other special-purpose, high-electrical-conductivity copper alloys are available with special properties. Among these are

1. *Zirconium-copper (UNS C15000).* This is an alloy containing about 0.15 percent zirconium. It has improved creep strength at elevated temperatures and a small decrease in electrical conductivity.
2. *Tellurium-copper (UNS C145xx).* The addition of small percentages of tellurium results in an alloy with a major improvement in machinability over pure copper while retaining an electrical conductivity of 90 percent IACS. Mechanical properties are moderately high as compared to those of copper.
3. *Sulfur-bearing copper (UNS C14700).* The addition of sulfur to copper in small percentages results in a substantial increase in machinability while retaining a relatively high electrical conductivity of about 96 percent IACS.

It can be seen that a wide choice of compositions are available, with electrical conductivities in the 95 to 101 percent electrical conductivity range. Wide overlapping of properties, both physical and mechanical, can lead to many trade-offs in selection of materials. Very often, the selection will be one of economics of fabrication weighed against material costs. Material suppliers can offer aid in selecting a specific material.

4.2.16.4 Brasses. Brass, by definition, is an alloy of copper and zinc, but, in some cases, trade names have been given to brasses that suggest that they are bronze, which is by definition an alloy of copper and tin. There exists a wide range of compositions. Some generalizations may be made about the effect of zinc on copper. Among them are the following:

1. Tensile strength increases with increasing zinc content up to about 30 percent zinc.
2. Electrical and thermal conductivity decreases as zinc content increases.
3. Ductility of soft annealed material increases as zinc content increases up to about 30 percent zinc. In the harder tempers, ductility decreases in lean zinc alloys but begins to increase at around 10 percent zinc.

As indicated, these are generalizations that are subject to modification by cold-working and annealing sequences that affect grain size. For critical forming or strength applications, it is desirable to work with the material supplier to select the specific set of properties tailored to the application and processing procedures.

4.2.16.5 Leaded brasses. Most of the brass compositions are available with lead added as a means of improving machinability. The lead exists in the matrix of the alloy as free lead, not as an alloy. The presence of lead results in production of fine chips in machining, thus producing a free-cutting condition. Lead contents vary from a nominal 0.5 percent to as high as 4.5 percent, with the highest percentage yielding the best machinability.

Lead has its detrimental qualities in that it reduces ductility. Problems may occur with the high-lead-content materials in forming operations. Terminals made from leaded alloys may crack in swaging and, in some cases, fracture during soldering. The latter problem is especially prevalent when the terminals are swaged to thick plastic terminal boards. Selection of one of the lower-lead-content alloys is a solution to this problem, although machinability may be reduced.

4.2.16.6 Phosphor bronzes. A series of bronzes containing 1 to 11 percent tin and 0.04 to 0.35 percent phosphorus is widely used for spring applications in electronics. These alloys are available in varying strengths up to a yield strength of 116,000 psi for the 10 percent tin alloy that has been cold-worked to the extra-spring-hard condition. However, this alloy has an electrical conductivity in the range of 11 percent IACS. The 1.25 percent tin alloy, on the other hand, has an electrical conductivity of about 48 percent, but its maximum attainable yield strength is 75,000 psi. This is an example of the tradeoff that sometimes must be considered in reduced electrical conductivity so as to increase strength.

4.2.16.7 Beryllium-copper (UNS C172xx). Copper, when alloyed with beryllium, forms an alloy that is capable of being strengthened by precipitation hardening. It is capable of attaining tensile strengths in the range of 200,000 psi by proper heat-treating and cold-working procedures. At this hardness level, it still possesses good electrical conductivity in excess of 22 percent IACS. As a result of this combination of high strength and good electrical conductivity, beryllium-copper has become a widely used material for electrical spring applications.

Because it is a precipitation-hardening alloy, beryllium-copper has processing advantages in forming. The material is subjected to a solution-annealing treatment, which leaves it in a relatively soft condition. Forming may be readily performed in this condition. A low-temperature aging treatment at about 600°F will result in increased strength with little distortion. For copper alloys, higher-strength alloys typically have the lower electrical conductivity. Effects on tensile strength and yield strengths brought about by variations in aging temperatures are shown in Fig. 4.20. The 600°F aging is usually specified, because the time at temperature is not critical. Note that the aging time at 600°F can vary by several hours with little effect on tensile properties. At higher temperatures, a few minutes of excess time may result in overaging, with a resulting drop in properties. However, it is practical to use shorter aging cycles at higher temperatures if proper controls of material condition and heat-treating time and temperature are exercised. The cold-working history of the material between solution treating and aging is important in the aging response. Determination of aging cycles by test is desirable when deviation is made from the 600°F aging temperature.

Figure 4.21 shows the effect of repeated stress on the cycles to failure in fatigue for a 2 percent beryllium-copper alloy. Note that, at 10^6 cycles, the stress

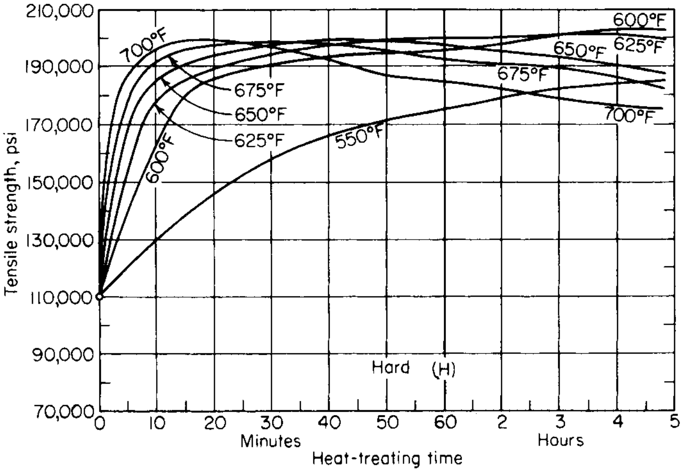

Figure 4.20 Effect of various aging times and temperatures on a typical 2 percent beryllium-copper alloy.

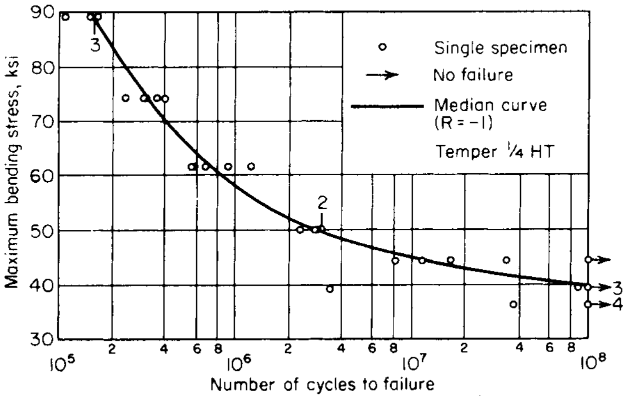

Figure 4.21 Effect of repeated stress on strength of a typical 2 percent beryllium-copper alloy.

is about 40,000 psi and that, even at 10^5 cycles, the tolerable stress level is less than 90,000 psi even though the material has a yield strength of 150,000 psi. These data point out the importance of considering the number of load applications when designing for repeated loads.

4.2.17 Magnesium alloys

Magnesium alloys have found acceptance primarily because they have the lowest density of any structural metal available today. The commonly used alloys have densities of about 0.065 lb/in^3, and the recently developed magnesium-lithium alloys have densities of less than 0.050 lb/in^3. These values may be compared to those of aluminum at approximately 0.100 and beryllium at approximately 0.066 lb/in^3. Poor corrosion resistance and poor formability preclude the use of magnesium alloys in many applications. Procedures are available for overcoming these problems and providing economical and functional units for a variety of applications. Magnesium alloys are used in many applications for reduction in weight as compared to aluminum alloys and for lower cost than typical beryllium structures.

4.2.17.1 Forms available. Magnesium alloys are available in nearly all forms, including sheet, plate, bar, forgings, and extruded shapes. Extrusion is generally used for shaping bar, tubing, and other shapes. Castings are also available, but in compositions specifically developed for casting. All types of castings, including sand, die, permanent-mold, and investment, are available. Investment castings are available in any of the other casting compositions.

4.2.17.2 Alloy designations. Magnesium alloys are designated by a coding system that indicates the approximate nominal alloy percents of the two major alloying elements. Designations for alloys consist of not more than two letters representing the two alloys present in the largest percentages, arranged in order of decreasing percentages. The letters are followed by numbers representing the percentage of the alloying element rounded off to the nearest whole number. The most frequently used letters are as follows:

- A = aluminum
- L = lithium
- E = rare earths
- M = manganese
- H = thorium
- Z = zinc
- K = zirconium

An example designation is AZ31, which indicates an alloy of magnesium in which the two main alloying elements are aluminum and zinc, as indicated by the AZ. The number 3 indicates 3 percent nominal aluminum, and the 1 indicates 1 percent zinc.

4.2.17.3 Alloy availability. The sheet alloy most commonly used is the AZ31 (3 percent aluminum, 1 percent zinc) composition. This is the general-purpose alloy for service near room temperature and is the most readily available alloy. The HK31 and HM21 alloys have been developed for improved strength at elevated temperature.

The LA141 alloy (14 percent lithium, 1 percent aluminum) is an example of the lowest-density class of alloys. Note that the strength of this alloy is relatively low, but the alloy possesses mechanical properties exceeding those of some commonly used metals such as annealed low-strength aluminum alloys. Other alloys based on the lithium-magnesium alloys are also available.

Extrusion alloys. Considerably more alloys are available as extrusions than as sheet alloys. The ZK60 alloys show the highest room-temperature properties of any magnesium alloys and compares favorably in terms of strength-to-weight ratio with the high-strength aluminum alloys. Compressive yield strength of magnesium alloy extrusions is significantly lower than the tensile yield strength of that same alloy. This is an excellent example of the directional properties found in certain alloys, as discussed previously. The magnitude of the difference between tensile and compressive yield strengths makes it mandatory that designers consider this difference in designs wherein stresses approach the yield strength.

Elevated-temperature properties of wrought magnesium alloys. As with all metals and alloys, the mechanical properties of magnesium are changed by temperature. Strength decreases as temperature increases, and ductility usually increases. Magnesium, being a relatively low-melting-point metal, can be drastically affected by moderately elevated temperature. For instance, the yield strength of AZ31B-H24 alloy decreases from 32,000 psi at room temperature to approximately 13,000 psi at 300°F. Alloys such as HK31A-H24 and HM21A-T8 are less affected by increases in temperature. HK31A-H24 has a yield strength of about 22,000 psi at 400°F, whereas HM21A-T8 retains a yield strength of about 13,000 psi at 600°F. Useful properties exist in selected magnesium alloys for moderately high-temperature service. Caution must be taken when using elevated-temperature properties, because the time at temperature, stress level, and the temperature itself also must be considered. Creep (deformation under a steady load) may occur well below the stress levels mentioned above. Consultation with suppliers for details about the properties for specific loading conditions and environments is recommended when designing for elevated temperatures. In some cases, tests simulating service conditions may be required.

4.2.17.4 Magnesium alloy castings. Magnesium alloy castings are poured in specific compositions primarily designed for casting. Usually, these alloys contain higher percentages of alloying elements than are found in wrought compositions.

Investment casting practice has been developed to the extent that wrought-type alloys can be cast for special applications. AZ31 alloy has been cast for applications in which brazing was required.

K1A alloy, an alloy possessing a high damping capacity, is another specialty alloy. This alloy has been used for parts for which vibration damping is required. It is an alloy with about 1 percent zirconium. This alloy is available from most investment casting foundries. Mechanical properties are lower than those of most of the other magnesium casting alloys.

As with other castings, the question of guaranteed mechanical properties should be agreed upon via specification or drawing call-out, or specified on a purchase order. Most standardized specifications show mechanical properties of separately cast test bars and often allow the properties of the actual castings to be well below those specified. It is obviously important that the designer know whether the specified values are for test bars or for the casting itself. However, there is danger of unnecessarily raising the cost of castings if the maximum possible strength is specified for every section of the casting. A more reasonable procedure is to specify strength requirements in the critically stressed areas of the casting. This will allow the foundry to arrange its pouring and chilling practices to attain maximum soundness and strength in the critical areas.

Elevated-temperature properties of magnesium castings. Similarly to the wrought alloys, magnesium casting alloys suffer decrease in strength as temperature increases. The normal aluminum-zinc alloys such as AZ91 lose strength rapidly as temperature increases. EZ33A alloy maintains 50 percent of its room-temperature properties at 600°F, while HK31A-T6 still has 81 percent of its room-temperature strength at 500°F and 50 percent at 700°F. HK31A is another example of an alloy which is normally considered a wrought alloy but has found use in castings.

4.2.17.5 Fabrication of magnesium alloys

Forming. Magnesium has a reputation of being difficult to form. However, under proper conditions, magnesium alloys may be formed to complex shapes by many techniques, including deep drawing. The use of elevated temperatures during forming is often necessary to accomplish such forming. Facilities that have been set up with heated dies have been very successful in forming magnesium alloys.

It is desirable, of course, to form material at room temperature for reasons of economy and convenience. Magnesium alloy AZ31A is capable of being formed as room temperature to a $2T$ radius (where T = metal thickness) in thicknesses of 1/8 in and less. This compares favorably with some of the aluminum alloys.

Joining. Magnesium can be joined by most conventional joining methods, both mechanical and metallurgical, as discussed below.

Riveting. Riveting of magnesium is done by normal riveting practice. The riveting material recommended is aluminum alloy 5056. This alloy is sufficiently close to magnesium alloys in galvanic potential that no serious dissimilar metal problem exists. It is advisable that rivets be installed with a barrier such as zinc chromate primer which is applied wet to the rivet just before driving.

Fusion welding. Fusion welding of magnesium alloys may be readily accomplished with the tungsten inert-gas (TIG) process or with the metal inert-gas (MIG) process. Filler rods must be selected in accordance with the alloy being welded. The aluminum-zinc alloys (AZ) are usually welded with AZ9Z alloy as filler. The high-temperature alloys are often welded with EZ33 rod but also are welded with rod matching the material composition. Selection of rod composition will depend on the joint efficiency required, ductility required, and so forth. The individual magnesium supplier should be consulted for each specific case.

Stress relieving of magnesium weldments. The alloys containing aluminum and zinc as alloying elements are subject to stress corrosion. Because welding nearly always results in some residual stress, stress relieving is required after welding. Typical cycles are (1) 500°F for 15 min for AZ31 alloy annealed sheet and extrusions and as-extruded AZ61, ZK60, and AZ80; (2) 300°F for 60 min for AZ31 hard-rolled and ZK60 in the aged condition; and (3) 500°F for 60 min for cast alloys.

Brazing. It is possible to braze magnesium by the dip method, utilizing brazing fluxes similar to aluminum brazing fluxes. Filler metal is usually a 12.5 percent aluminum alloy. The removal of flux is a must, because the residues of flux are extremely corrosive to magnesium alloys. Most magnesium alloys may be brazed. A brazing process should be specified only after careful consultation with magnesium suppliers.

4.2.18 Nickel and nickel alloys

Nickel alloys are characterized by good strength, corrosion resistance, and high ductility. The metal nickel has relatively good electrical conductivity, making it useful for electrical conductors for specialized applications. The magnetostrictive properties of nickel and high-nickel alloys make them applicable to various devices such as ultrasonic transducers. Nickel and nickel alloys have Curie temperatures that vary with alloy content. This transition from magnetic to nonmagnetic behavior has been used in control devices. The series of alloys based on nickel-copper are known as Monels.* These materials show exceptional corrosion resistance in saltwater immersion service. Some of these alloys are age hardenable, notably the alloy K-500 and 500. The Inconel series of alloys is based primarily on nickel plus chromium plus iron with minor additions of other alloying elements. These alloys have exceptionally good elevated-temperature properties. Such alloys are useful at temperature ap-

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* Registered trademark of Inco Alloys International.

proaching 2000°F. A specialty alloy of beryllium and nickel is age hardenable to strengths in excess of 200,000 psi. This material retains good strength at 600°F. It has found use as a spring material.

4.2.18.1 Forms available. Nickel and nickel alloys are available in most wrought forms. This includes all section sizes from ultra thin sheet and fine wire to heavy plate and forgings.

4.2.18.2 Fabrication. Nickel and nickel alloys have exceptionally good fabrication properties, as discussed below.

Forming. The ductility of nickel alloys makes forming by most conventional techniques extremely favorable.

Joining. Welding is practical for all nickel alloys by arc, gas, and resistance methods. Welding of nickel alloys to most steels as well as to some copper alloys is often performed.

Brazing. Brazing with the silver brazing alloys, copper, and nickel-base brazing alloys is readily accomplished by furnace, torch, induction, and resistance brazing.

4.2.18.3 Physical properties of nickel alloys. Table 4.19 shows values of a variety of properties of nickel alloys. The variety of magnetic and electrical properties obtainable by alloying makes nickel alloys extremely interesting to the electronics engineer.

4.2.18.4 Mechanical properties of nickel alloys. Nickel alloys may be supplied in various conditions (cold-drawn, annealed, and so on). These conditions will have ranges for properties. The ranges will depend on section size, manufacturing procedures, and heat-treating practice. Caution should be exercised when selecting materials of large section sizes, because it is likely that the highest-strength alloys will not be readily available.

4.2.19 Titanium and titanium alloys

The chief attributes of the titanium family are excellent corrosion resistance, moderate density, and good strength, especially when considered on a strength-weight basis. Titanium alloys have densities about 60 percent of steel's, making the high-strength titanium alloys competitive with the high-strength steels when considered on a specific-strength (strength/density) basis. At temperatures around 600°F, titanium alloys surpass practically all other metals in reducing weight.

The electrical and thermal conductivities of titanium and its alloys are very low as compared to those of the aluminum, copper, and magnesium alloys.

TABLE 4.19 Physical Properties of Nickel and Nickel Alloys[*]

Designation	Density, lb/in^3	Modulus of elasticity, psi × 10^{-6}		Melting range, °F	Specific heat at 70°F, Btu/(lb)(°F)	Thermal expansion, in/(in)(°F) × 10^{-6}		Thermal conductivity, Btu/(hr)(ft^2)(°F/in)		Electrical resistivity, Ω/cir mil/ft		Curie temperature, °F		Permeability @ 70°F (H = 200)		Poisson's ratio
		Tension	Torsion			70–200°F	70–500°F	70°F	500°F	70°F	500°F	Annealed	Age-hardened	Annealed	Age-hardened	
Nickel 200	0.321	30.0	11.0	2615–2635	0.109	7.4	7.9		374	57	126	680				0.31
Nickel 201	0.321															
Nickel 204	0.321	29.2				7.4	7.8			65		770				
Nickel 205	0.321									57						
Nickel 211	0.315					7.4	7.9	306	296	102	195					
Nickel 220	0.321															
Nickel 230	0.321															
Nickel 233	0.321															
Nickel 270	0.321	30.0		2650	0.11	7.4	7.8	655		43	125	667				
Permanickel alloy 300	0.316	30.0	11.0		0.106	6.8	7.9	400		94.5		600	563			
Duranickel alloy 301	0.298	30.0	11.0	2550–2620	0.104	7.2	7.7	165	211	255	310	60–120	200			0.31
Monel alloy 400	0.319	26.0	9.5	2370–2460	0.102	7.7	8.7	151	204	307	342	20–50				0.32
Monel alloy K-500	0.306	26.0	9.5	2400–2460	0.100	7.6	8.2	121	167	370	382	<–210	<–150	1.001	1.002	0.32
Monel alloy 501	0.306	26.0	9.5	2400–2460	0.100	7.6	8.2	121	167	370	382	<–210	<–150	1.001	1.002	0.32
Inconel alloy 600	0.304	31.0	11.0	2500–2600	0.106	7.4	7.8	103	127	620	639	–192		1.010		0.29
Inconel alloy 604	0.305					6.8	7.6	101	126	666	687	<–320		1.004		
Inconel alloy X750	0.298	31.0	11.0	2540–2600	0.103	7.0	7.4	83	104	731	754	–225	–193	1.002	1.0035	
Inconel alloy 751	0.298	31.0	11.0	2540–2600												
Inconel alloy 800	0.290	28.0	11.0	2475–2525	0.12	7.9	9.0	80	109	595	662	–175		1.009		0.30
Inconel alloy 801	0.287	29.0				8.1	9.0									
Inconel alloy 804	0.286	28.0				8.0				638		<–320		1.003		
Inconel alloy 825	0.294	28.0		2500–2550		7.8	8.4	77	103	678	719	<–320		1.005		
Ni-span-C alloy 902	0.293	24–29	9–10	2650–2700	0.12	4.2	6.0	84	114	611		340	380			

[*] SOURCE: NASA contrace NAS8-21233, Final Report.

These low values are definite disadvantages in many applications but an advantage in applications where thermal isolation is desired or induced current from electric fields is to be minimized. Thermal expansion rates are slightly lower than for steels but generally are close enough to cause no appreciable problems. Physical properties are shown in Table 4.20. Titanium is available in commercially pure form (99 percent minimum Ti) and in a number of alloyed compositions.

Commercially pure titanium is available in several purities. This material ranges from 60,000 to 80,000 psi in tensile strength, depending n purity. It has the best heat-corrosion resistance, weldability, and formability of any of the titanium alloys. The pure metal is generally lowest in cost.

4.2.19.1 Titanium alloys. A number of alloying elements are used to enhance the properties of titanium. These include aluminum, vanadium, iron, manganese, tin, chromium, and molybdenum. Alloys are most often designated by nomenclature that starts with Ti, the chemical symbol for titanium, followed by a number that represents the nominal percentage of an alloying element, followed by the chemical symbol of the element. For example Ti6Al4V is titanium alloy containing 6 percent aluminum and 4 percent vanadium.

Three basic metallurgical types of alloys exist, namely, *alpha, alpha-beta,* and *beta*. The alpha type consists of alloys that retain the hexagonal crystal structure as found in pure titanium. On heating to 1625°F, unalloyed titanium transforms to a body-centered structure that is designated as the beta phase. Through the selection of alloying elements, the beta phase can be stabilized to the extent that it will exist at room temperature. Some alloys are alloyed to stabilize the entire structure in the beta phase at room temperature and thus are obviously called beta alloys.

Through proper selection of alloying elements, alloys have been developed that consist of a combined alpha and beta two-phase structure at room temperature. These alloys retain some of the advantages of both the alpha and beta phases and also render such alloys capable of heat treatment to higher strengths. Heat treatment consists of heating to temperatures that are high enough to transform the alpha phase to beta. Rapid cooling suppresses the natural transformation of beta to alpha. On subsequent aging, there is a transformation of some of the beta to alpha. This alpha is distributed throughout the beta matrix to give a fine structure that results in increased strength.

Some beta alloys can be heat treated by aging as well. During aging, fine particles of alpha and intermetallic compounds are precipitated out to provide strengthening. By alloying, the strength of titanium can be raised considerably above the strength of the unalloyed material. Yield strengths above 150,000 psi at room temperature are attainable with available alloys. Several factors other than mechanical properties must be considered when selecting an alloy. One of these is the availability of the alloy within the time required and in the quantity required. Metal distributors do not tend to stock many titanium and alloy products. The method of fabrication will also influence selection. Many of the alloys are not considered weldable, as welds are brittle.

TABLE 4.20 Typical Physical Properties of Titanium Alloys

Nominal composition, % (bal. Ti)	Density, lb/in^3	Thermal expansion mean coefficient per °F × 10^{-6}			Thermal conductivity, Btu/(hr)(ft)(°F)		Instantaneous specific heat, Btu/(lb)(°F)		Electrical resistivity, μΩ-cm		Elastic moduli, psi × 10^{-6}	
		RT to 200°F	RT to 600°F	RT to 1000°F	RT	800°F	RT	800°F	RT	800°F	*B*	*G*
99.5 Ti	0.163	4.8	5.2	5.5	9		0.124		57		14.9	6.5
99.2 Ti	0.163	4.8	5.2	5.5	9.5		0.125		56		14.9	6.5
99.0 Ti	0.163	4.8	5.2	5.5	9.5–11.5	10.5	0.125	0.151	48–57	117.7	15.0	6.5
99.0 Ti	0.164	4.8	5.2	5.5	9.8–10.1	10.0	0.129	0.155	55–60	122.3	15.1	6.5
98.9 Ti	0.164	4.8	5.2	5.5	9.8		0.129		58		15.5	6.5
0.15–0.20 Pd	0.163	4.8	5.1	5.4	9.5		0.125		56.7		14.9	6.5
Alpha alloys												
5 Al, 2.5 Sn	0.161–0.162	5.2	5.3	5.3	4.5	7.2	0.125	0.152	157	180	16.0	7.0
5 Al, 2.5 Sn (low O)	0.161	5.2	5.3	5.4	4.5		0.125		157		16.0	
5 Al, 5 Sn, 5 Zr	0.166										16.0	
7 Al, 12 Zr	0.165										16.5	
7 Al, 2 Cb, 1 Ta	0.159										17.7	
8 Al, 1 Mo, 1 V	0.158	4.7	5.0	5.6					199	203	18.5	
Alpha-beta alloys												
8 Mn	0.171	4.8	5.4	6.0	6.3	9.0	0.118	0.152	192	140	16.4	7.0
2 Fe, 2 Cr, 2 Mo	0.171										16.7	
2.5 Al, 16 V	0.165											
											15.0	(aged)
3 Al, 2.5 V	0.162										15.5	
4 Al, 4 Mn	0.163	4.9	5.1	5.4	4.2	7.4	0.126	0.159	153	172	16.4	7.3
4 Al, 3 Mo, 1 V	0.163	5.0	5.3	5.5	3.9	6.8	0.132	0.142	165		16.5	7.0
5 Al, 1.5 Fe	0.162–	5.2	5.3	5.5							16.8	
2.75 Cr	0.163										17.6	(aged)
5 Al, 1.5 Fe, 1.4 Cr	1.162–	5.2	5.5	5.7	4.7	7.0			163	180	16.5	6.3
1.2 Mo	0.163										17.0	(aged)
6 Al, 4 V	0.160	4.9	5.1	5.3	4.2	6.8	0.135		171	187	16.5	6.1
6 Al, 4 V (low O)	0.160	5.3	5.3	5.3			0.135		171		16.5	6.1
6 Al, 6 V, 2 Sn	0.164	5.0	5.2	5.3	4.2		0.155		157		15.0	
1 (Fe, Cu)									157	170	16.5	(aged)
7 Al, 4 Mo	0.162	5.0	5.2	5.6	3.7	7.0	0.123	0.151	175	183	16.2	6.5
											16.9	(aged)
Beta alloys												
1 Al, 8 V, 5 Fe	0.168											
8 Al, 13 V, 11 Cr	1.175–	5.2	5.6	5.9	4.0	8.0	0.120	0.198	153		14.2	6.2
	0.176								142		14.8	(aged)

4.2.19.2 Corrosion resistance of titanium alloys. One of the major attributes of titanium alloys is corrosion resistance. The major commercial applications of these materials have been in the chemical field where the superior resistance to chemical attack has resulted in major economies as a result of the increased longevity of titanium parts as compared to that of other structural metals. Room-temperature atmospheric and saltwater environments are withstood well by titanium alloys. Stress corrosion in the presence of chlorides above 600°F is a problem, but such conditions are uncommon in electronic equipment, so this is not a serious drawback.

Titanium is the noble metal in a galvanic couple with most structural materials except stainless steel and Monel. Protection to prevent a galvanic couple may be needed when titanium is attached to other metals, especially aluminum alloys, magnesium alloys, or beryllium. As for most galvanic couples, consult MIL-STD-889 for guidance.

4.2.19.3 Contamination. Titanium and its alloys are subject to pickup of hydrogen, oxygen, and nitrogen, which will generally result in decreased ductility. Such contamination is most likely to occur at elevated temperatures. Thus, caution must be used in selecting atmospheres for heat treatment, especially above 1200°F. Selection of heat-treating atmospheres that are rich in one or more of the deleterious elements should be avoided. Inert gases such as helium or argon are most satisfactory as protective atmospheres, whereas a vacuum provides good protection and, in some cases, may be used to remove hydrogen that has been picked up from other sources. Plating and pickling are also sources of hydrogen pickup. Welding of titanium without fill shielding is another source of oxygen and nitrogen contamination.

4.2.19.4 Forms available. Titanium alloys are available in nearly any wrought form. Casting developments are underway, but casting has not become a common technique. Sheet, plate, bar, wire, strip, tubing, and extrusions are available in one alloy or another. Stock from a metal distributor may not be reliable, depending on the demand in a particular geographic region. Consultation with suppliers on the availability of alloys and forms available in that alloy is recommended before specifying a material for production.

4.2.19.5 Fabrication of titanium. Conventional processes are used for fabricating titanium parts. However, special precautions and revised techniques are sometimes required.

4.2.19.6 Forming. Titanium alloys have reasonable formability, similar to many other high-strength materials. Bend radii on commercially pure annealed high-purity sheet may be as low as 1 times the sheet thickness (1*T*). The high-strength alloys in the solution-treated and aged condition may require radii as great as $8T$ or more. Springback is particularly troublesome in titanium and its alloys because of their high yield strengths combined with relatively low elastic moduli. Hot-forming is often used with titanium alloys to minimize springback and decrease bend radii. Caution must be used in selecting temperatures for forming, because temperatures above the aging temperature will overage the material, resulting in lower strength.

4.2.19.7 Welding. Tungsten inert-gas welding of the weldable alloys is practical. The major precaution is that the heated weld area must be shielded from the atmosphere. Shielding gas should be supplied to both sides of the weld, and a trailing shield of gas is required to protect the weld during cooling. It may often be desirable to weld in an enclosure that is filled with inert gas. Glove box chambers for this purpose are commercially available.

Mechanical properties of welds are excellent. Most weldable alloys can be welded to 100 percent joint efficiency. The pure titanium grades and the alpha alloy grades are all weldable with good resulting mechanical properties and ductility. Certain of the alpha-beta alloys can be satisfactorily welded, but others are subject to formation of brittle welds. Caution should be used when specifying welding of these alloys, and the advice of materials suppliers should be sought on selection of welding rod, joint design, and welding procedures. Resistance weldability of titanium is excellent.

4.2.20 High-density materials

Although, to a great extent, electronics engineers are interested in producing lightweight equipment, there are occasions when a high-density material is required so as to place a concentrated mass in a small volume. In some instances, the requirement for low thermal expansion and high thermal conductivity supersedes the weight requirement. A typical application is a counterweight.

Three categories of metals are available for these purposes. Of course, the moderately heavy metals, such as steels, nickel alloys, and copper alloys, can be used for such purposes if space is available. We will concentrate on the lead, tungsten, and depleted uranium metals, because they have higher densities than the aforementioned metals but still have reasonable economic feasibility as compared to high-density precious metals such as gold.

4.2.20.1 Lead and lead alloys. Lead, with a specific gravity of 11.35 g/cc (0.41 lb/in^3) and a relatively low cost, is often a choice for counterweights. The low melting point of lead allows it to be cast using low-cost techniques, resulting in further economies.

The major disadvantage of lead is its low strength. The yield strength of relatively pure lead is around 800 psi, thus making it unsuitable for load-carrying applications. The creep rate of lead at room temperature is appreciable at stresses of 300 psi.

Antimony, when alloyed with lead in percentages of 1 to 9 percent, can appreciably increase the strength of lead. These alloys are also precipitation hardenable by heat treatment. For the 4 percent antimony alloy, values of above 11,000 psi tensile strength have been reported. As-cast values of around 3,500 to 4,000 psi tensile strength have been found. Creep strengths do not appear to be drastically improved, however, indicating that sustained loads should be avoided.

Recently, dispersion-hardened lead has been developed. This material is available in the dispersion-hardened condition but will lose most of its favorable properties if melted.

4.2.20.2 Sintered tungsten. Sintered tungsten material is available with specific gravities in the range of 17 g/cc. These materials are usually tungsten particles mixed with other materials such as copper or nickel, after which they are compacted and sintered. The metals other than tungsten melt and braze the tungsten particles together. A wide variety of proprietary materials are available. Density and mechanical properties will vary, depending on the percentage of metals other than tungsten used.

The materials are available in bars and may be furnished in relatively complex shapes if quantities are sufficient to amortize dies.

4.2.20.3 Depleted uranium. This material, with a density in the range of 18.5 g/cc, has become available. With mechanical properties similar to those of low-carbon steel, it offers good structural properties. It is also capable of being cast to shape and worked by conventional tools, making economies of manufacture possible. Corrosion resistance of depleted uranium is poor, so it requires corrosion protection by the application of coatings.

4.2.21 Refractory metals

Refractory metals, which are noted for their high melting points and ability to be useful at high temperatures, find some uses in electronic equipment at relatively low temperatures. These uses often are based on a combination of physical and mechanical properties. In addition, some of the metals have extremely good resistance to acids.

Table 4.21 summarizes the physical and mechanical properties of four important refractory alloys. It can be seen that a variety of properties are available among the metals tungsten, tantalum, molybdenum, and columbium. Alloys are available that modify these properties.

4.2.21.1 Mechanical properties. The most important of these alloys' mechanical properties is the useful strength that exists at elevated temperatures as high as 1000°C. This has been of major importance in consideration of these materials and structures.

4.2.21.2 Modulus of elasticity. The variation in modulus is wide, with tungsten possessing a value about twice that of steel, whereas columbium's modulus is

TABLE 4.21 Typical Properties[*] of Refractory Alloys

Property	Tungsten	Tantalum	Molybdenum	Columbium
Atomic number	74	73	42	41
Atomic weight	183.92	180.88	95.95	92.91
Atomic volume	9.53	10.9	9.41	10.83
Mass				
Density at 20°C:				
g/cc	19.3	16.6	10.2	8.57
lb/in^3	0.697	0.600	0.368	0.31
Thermal properties				
Melting point, °C	3400	2996	2625	2415
Boiling point, °C	5900–6700	7400	5560	3300
Linear coefficient of expansion per $°C \times 10^{-6}$	4.0	6.5	5.45	6.89
Thermal conductivity at 20°C, $cal/(sec)(cm^2)$	0.399	0.130	0.349	0.13
Specific heat, cal/(g)(°C)	0.34 (100°C)	0.036 (0°C)	0.061 (20°C)	0.065 (0°C)
Electrical properties				
Electrical conductivity, % IACS	31	13.9	36	13.3
Electrical resistivity, μΩ-cm	5.48 (0°C)	12.4 (18°C)	5.17 (0°C)	14.2
Temperature coefficient of electrical resistivity per °C	0.00482 (20–100°C)	0.00382 (0–100°C)	0.0047 (20–100°C)	0.0395 (0.600°C)
Mechanical properties				
Tensile strength, ksi:				
At room temperature	100–500	100–150	120–200	75–150
At 500°C	175–200	35–45	35–65	35
At 1000°C	50–75	15–20	20–30	
Young's modulus of elasticity, $psi \times 10^{-6}$	59	27	46	12–15
At room temperature				
At 500°C	55	25	41	6.5
At 1000°C	50	22	39	
Working temperature, °C	1700 down	Room	1600	Room
Recrystallization temperature, °C	1300–1500	1050–1500	900–1200	900–1300
Stress-relieving temperature, °C	1200	900	800	800
Nuclear				
Cross section, thermal neutrons, barns/atom	19.2	21.3	2.4	1.1

[*] Ranges only; data vary with type of sample and previous work history.

little higher than that of aluminum. The retention of high-modulus values at elevated temperatures is another factor in the use of these materials at elevated temperatures.

4.2.21.3 Density. The high density of tungsten and tantalum has resulted in their use as counterweights and as radiation shields. Molybdenum and columbium are slightly more dense than steel. The low thermal-expansion rates of tungsten and molybdenum make them good materials for use with some glasses and ceramics. Tantalum and columbium have expansion rates that are relatively low as compared to those of steels.

4.2.21.4 Electrical properties. The electrical properties of these metals, especially tungsten and molybdenum, make them applicable as electrical conductors. On the other hand, these alloys are also used as heating elements.

The characteristics shown in Table 4.21 gives a general view of the properties to be expected in alloys of this group. Alloys based on these metals will generally retain the properties of the base metal in terms of density, modulus of elasticity, and high temperature resistance. Attention should be paid, however, to the effect of alloying on electrical conductivity and thermal conductivity, as well as thermal expansion.

4.2.22 Precious metals

The precious metals find rather frequent use in electronic equipment, generally for their physical and surface properties rather than for their mechanical properties. Physical properties such as electrical conductivity account for the use of such alloys as gold and silver. Their resistance to form surface compounds that interfere with electrical and/or optical properties of surfaces accounts for the use of such materials as gold, rhodium, and platinum.

Table 4.22 gives some of the physical properties of the most frequently used precious metals. These are typical figures for the pure metals. Most of these metals may be alloyed with other metals to enhance certain properties, but often with major effects on other properties. The form of the metal must also be considered. This is especially true of the electroplated form, because many of these metals find their major use as electroplates. Many electroplates have additives that are present for purposes of aiding in throwing power, smoothness, or luster, or for other reasons. These additives may have major effects on such properties of the deposited metal. In addition, many electroplates are actually alloys that may have drastically different physical and mechanical properties from those quoted for pure wrought metals. The density of electroplates varies somewhat also and will result in property variations.

4.2.22.1 Silver. Silver has the highest electrical conductivity and thermal conductivity of any of the metals. It has found use as electrical conductors and as

TABLE 4.22 Physical Properties of Precious Metals

Metal	Density, lb/in^3	Melting temp., °F	Coefficient of linear expansion per °F × 10^{-6}	Thermal conductivity @ 212°F, Btu/(hr) (ft^2)(°F/ft)	Specific heat, Btu/(lb)(°F)	Electrical resistivity @ 32°F, μΩ-cm
Platinum	0.775	3217	4.9	42	0.031	9.83
Palladium	0.434	2826	6.5	41	0.058	10.0
Rhodium	0.447	3560	4.6	50	0.059	4.51
Ruthenium	0.441	4190	5.1	—	0.057	7.6
Iridium	0.813	4447	3.8	34	0.031	5.3
Osmium	0.82	5432	3.6	—	0.031	9.5
Gold	0.698	1945	7.9	172	0.031	2.19
Silver	0.379	1761	10.9	242	0.056	1.47

a contact material. Probably the largest use of silver is as an electroplate on various types of pins, terminals, and contacts. The tarnishing of silver by sulfur compounds, which are present in most industrial atmospheres, is a major problem in the use of silver as a contact alloy or as a finish for terminals that must be soldered. The sulfide of silver interferes with electrical contact and makes soldering difficult. As a result, most silver surfaces are protected with an overplate of gold, which will protect the surface from sulfide formation. Problems have been encountered with this system of protection, because thin or porous electroplates do not offer sufficient protection to prevent sulfiding through the gold electroplate. At present, 50 millionths of an inch of gold is considered sufficient.

Silver is a low-strength material that is not suitable for most structural applications. Alloying with copper is a means of increasing the strength of silver. At 10 percent copper, which is known as *coin silver,* electrical resistivity increases to 2.2 Ω-cm as compared to about 1.6 Ω-cm for pure silver. The tensile strength of the 10 percent copper alloy in the annealed condition is almost twice that of silver in the annealed condition.

4.2.22.2 Gold. Gold is used widely as an electroplate to give corrosion resistance, to provide a contact surface with low resistance, and, in some special cases, as a conductor material. The low strength of gold makes it of little use as a structural or wear-resistant material. Alloys are available in both wrought and cast form and in the electroplated form. Alloys such as cobalt may increase the resistivity quite drastically. For instance, 1 percent cobalt increases the resistivity of gold by 710 percent.

4.2.22.3 Rhodium. The high reflectivity and low electrical surface resistance of rhodium, combined with its high hardness and the stability of the surface under corrosive conditions, make rhodium highly suitable for contact surfaces and mirrors. Rhodium is primarily applied by electroplating.[8]

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