

ENGINEERING MATERIALS

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Metals and alloys

Ferrous

- Cast irons, cast steels, and powder metals
- Carbon and low alloy steels
- Stainless steels
- Tool steels
- Maraging steels

Nonferrous

- Aluminum alloys
- Titanium alloys
- Alloys of copper, tin, nickel, beryllium, cobalt, magnesium, zinc, lead
- Refractory alloys: niobium (a.k.a. columbium), tantalum, molybdenum, tungsten, rhenium
- Superalloys
- Shape memory alloys
- Amorphous metals

Ceramics

Polymers

- Thermosetting
- Thermoplastic
- Elastomers

Composites

Natural composites:

- Wood and bone
- Concrete (portland cement)

Engineered composites:

- Metal matrix composites (MMC's)
 - Continuous fiber, short fiber (a.k.a. whisker), particulate
- Ceramic matrix composites (CMC's)
 - Continuous fiber, short fiber (a.k.a. whisker), particulate
- Fiber-reinforced-plastic composites (FRP)
 - Chopped (short) fiber, continuous fiber

CAST IRONS AND CAST STEELS

Most metal alloys can be cast. But due to grain structure effects, shrink rates, high viscosity (low fluidity), etc. many are not. Specific alloys have been engineered for the sake of casting.

Iron itself has been used for about 6000 years to form tools. Obviously, early users of iron were unfamiliar with methods to refine and purify the ore, so the quality was not of “industrial” grade. Steel was born in the 19th century when refining methods were developed to reduce impurities. Ferrous alloys could then be used as an engineering material.

Cast Irons

Typically contain between 2 to 4% carbon, and 1-3% silicon

4 types: Gray, Malleable, White, Ductile

May contain significant amounts of alloying elements or not.

Can be metastable Fe-Fe₃C or equilibrium Fe-graphite systems.

Fe-Fe₃C cast irons are often referred to as *white cast iron* because of the fracture surface’s white appearance (fracture occurs along the iron carbide plates).

Graphite cast irons are often referred to as *gray cast iron* because of the fracture surface’s gray appearance (fracture occurs along the graphite plates/flakes).

As the name implies, products made from cast irons are cast into final shape, not worked.

Gray Cast Iron

Contain between 2 – 4% C and more than 1% Si

Carbon is in the form of graphite flakes

Designation: ASTM A48 classes (20-60) – classes specify properties, composition, etc.

Properties

- brittle (no σ_{ys}) low ductility, low toughness
- σ_{UT} 20-60 ksi
- Very good σ_{UC} ($3 - 5 \times \sigma_{UT}$)
- Stiffness is non-linear
- $S_{end} \sim 0.4 \sigma_{UT}$
- Excellent wear resistance for metal-metal contact (graphite “lubricates”) – should be used to wear against hardened steel.
- Very resistant to seizing

Gray Cast Iron Applications

- machine bases / supports (vibration damping)
- pipes (fair corrosion resistance)
- wear resistance
 - gray cast iron gears mated with hard steel pinions
 - engine blocks

Malleable Cast Iron

Contain between 2-3% C and 1-2% Si

Designation: ASTM A47 grade *abcde*, where *abc* indicates minimum acceptable yield strength ($abc = 325 = 32.5 \text{ ksi}$) and *de* is elongation: $de = 20 = 20\% \text{ EL}$

Malleable cast irons are heat treated to increase ductility. Usually H.T. White Iron.

Carbon forms graphite nodules

Properties

- similar to gray cast iron, except ductility up to 20% EL
- $E \sim 25\text{-}27 \text{ Mpsi}$
- Excellent machinability
- $S_{\text{end}} \sim 60\% \sigma_{\text{ut}}$
- $\sigma_{\text{uc}} = 4 \sigma_{\text{ut}} \sim 400 \text{ ksi}$
- Very good wear resistance

Applications:

General applications at room to elevated temperature

Ductile Cast Iron (a.k.a. nodular cast iron)

Contain between 3-4% C, 2-3% Si, + Ni

Carbon forms nodular or spherical graphite

Designation: ASTM A536 grades 1-5;

Grade 5 (60-40-18)

Grade 4 (65-45-12)

Grade 3 (80-55-06)

Grade 2 (100-70-03)

Grade 1 (120-90-02)

--- the number after the grade indicates material properties: (60-40-18 has min. tensile strength of 60ksi, min. yield strength of 40ksi, and 18% elongation)

There are several other less widely used specifications (A 395, A 439, A 476, A 571, A 715).

Properties

- similar to gray cast iron
- Can be very ductile
- Good impact properties

Applications

- Pressure containing parts such as valves and pump bodies
- Gears, pinions, slides

White Cast Iron

Contains between 2-4% C, 0.5-2% Si, 0.5% Manganese, + other various

Carbon does not form graphite, rather it forms cementite (Fe_3C)

Designation: ASTM A 532 (wear resistant white cast iron)

Properties

- very wear resistant
- some white cast irons have good corrosion resist
- some good creep resistance

Summary of Cast Irons

Generally

- excellent wear resistance
- excellent compressive strength
- some are brittle, some have moderate ductility
- lower stiffness than steel
- better corrosion resistance than steel
- poor weldability

Cast Steels

Generally

- higher stiffness than cast irons
- much higher toughness than cast irons

Casting is the first step in production of wrought steel, but most steels are then drawn, rolled or in some other way cold or hot worked and heat treated before being sold as raw material.

Steel castings are less common than cast irons. Steel is difficult to cast because:

- high melting point
- high shrink rates
- less fluid than cast iron
- but better weldability

Most cast steels have ~0.5% Si & 0.5 – 1% Mg to increase fluidity

Designation: ASTM A148, with 15 various grades that have similar properties to wrought steels AISI / SAE 1030, 4130, etc.

Applications

- widely variety as is with wrought steel
- can make complex shapes more economically than with wrought

Powder Metals

Metal powders – powder is coalesced under high temperature and pressure

~ 2/3 of P/M are ferrous alloys, 10% are copper alloys, 10% are aluminum alloys

Applications

- small parts, typical, but can be large
- competitive with castings & forgings

CARBON AND LOW ALLOY STEELS

As previously discussed, steels can be formed by casting and powder metallurgy. The subsequent sections discuss wrought steels.

Carbon steels (a.k.a. plain-carbon steels)

Contain 0.03-1.2% C, 0.25-1.00% manganese, and minor amounts of other elements.

Generally, carbon steels:

- cannot be strengthened above 100ksi
- are not very hardenable
- poor corrosion properties
- poor impact toughness at low temperatures (relatively high ductile to brittle transition temperature).

Carbon and low alloy steels can be further classified as low, medium or high carbon.

< 0.25 wt% C, low carbon

0.25 % < C < 0.60%, medium carbon

0.60% < C < 1.4%, high carbon

The higher the carbon content, the stronger, less ductile, less tough the steel becomes.

Low alloy steels

Additional elements are added to improve various properties: manganese, nickel, chromium, molybdenum, tungsten, vanadium. A total of about 10% (no definitive cut-off) of alloying elements is considered to be “low alloy”.

The cost of low alloy steels is higher than plain-carbon steels.

Within the category of “low alloy” is a widely used group referred to as HSLA steels (high strength, low alloy). These are low alloy steels that have alloying elements added primarily for the sake of increasing strength. They typically have low carbon content (<0.25% C).

Carbon and low alloy steels:

Designations: AISI / SAE YYXX

YY – 1st Digit – Major alloy elements

2nd Digit – indicates alloy elements

XX – 0.XX wt % C

10xx – general purpose plain carbon steel

11xx – “free machining” – easy to machine

12xx – “free machining” – easy to machine

13xx – manganese (1.75%)

15xx – manganese (1.00%)

2xxx – nickel

3xxx – nickel + chromium

40xx – molybdenum

41xx – chromium, molybdenum (a.k.a. chrome-moly steel)

43xx – nickel, chromium, molybdenum

etc. (see any basic text on materials for a long list of steels)

ASTM also has specifications for carbon and low alloy steels. The “numbering” schemes do not necessarily have significance. For example, ASTM A 36 covers structural steels. However, for many steels, the grade is the same as the AISI designation. For example, ASTM A 29 grade 1020 is AISI 1020.

Together, ASTM and SAE have developed a Unified Numbering System (UNS). For carbon and alloy steels, these are virtually the same as the AISI/SAE designation, except they are preceded by the letter G and a zero is added at the end. AISI 1020 = G10200.

There are also numerous trade names used for proprietary steels.

Within the AISI/SAE designations are modifications. For high production runs where consistency in hardness is important, tighter controls over the acceptable range of composition may be required. AISI/SAE designations with an H at the end (for example, AISI 4130H) have tighter limits on composition ranges and hence have less variability in hardening characteristics.

Applications:

- AISI 1010 – sheet and strip for wire, rods, nails, screws and concrete reinforcing bars
- AISI 1020 – plate and structural sections, shafts, gears
- AISI 1040 – crankshafts, bolts, high-tensile tubing, shafts
- AISI 1080 – chisels, hammers, music wire
- AISI 1095 – knives, hacksaw blades, high-tensile wire
- AISI 1340 – high strength bolts
- AISI 4063 – springs, hand tools
- AISI 4140 – aircraft engine gears
- AISI 4340 – bushings, tubing, heavy sections of aircraft landing gears and truck parts
- AISI 4620 – transmission gears, chain pins, shafts, roller bearings
- AISI 5140 – automotive transmission gears
- AISI 5160 – automobile coil and leaf springs
- AISI 6160 – shafts, pistons, gears
- AISI 8620 – transmission gears

Most of these steels are available in cold worked (cold drawn, cold rolled, cold finished) or hot rolled conditions as well as a variety of heat treat conditions. High carbon steels are almost always used in quenched and tempered condition (i.e. tempered martensite).

STAINLESS STEELS

Must have at least 10% chromium to be considered to be stainless

Have excellent corrosion resistance in an oxidizing environment – but poor in a reducing environment. Specific alloys have excellent corrosion resistance in specific environments.

4 types: ferritic, martensitic, austenitic, PH (precipitation hardened)

Ferritic: BCC ferrite, usually less than 0.20% C, 10-20% Cr
Properties: poor weldability, high notch sensitivity (low toughness), less susceptible to stress corrosion cracking than most other stainless steels.
Applications: elevated temperature and non-rusting architectural parts

Martensitic: 0.6-1.2% C, 12-18% Cr
Applications: non-rusting tools and structural parts

Austenitic: 3 major alloying elements 16-20% Cr, 8-24% Ni, low carbon content
Non-magnetic
Applications: used for excellent chemical resistance.

PH (precipitation hardened) – can be martensitic, semi-austenitic or austenitic. Can be fabricated at low strength and then precipitation hardened to have high strength. Application requiring high strength and chemical resistance.

Applications (AISI designations):

Ferritic SS:

409 – automotive exhaust components, chemical tanks
446 – Valves (high temperature), combustion chambers

Austenitic SS:

304 – chemical and food processing equipment, cryogenic vessels
316L – construction (weldable), orthopedic

Martensitic SS:

410 – rifle barrels, cutlery, jet engine parts
440A – cutlery, bearings, surgical tools

PH (precipitation hardened):

17-7PH – springs, knives, pressure vessels

TOOL STEELS

Tool steels are extremely hard and tough. They were originally developed to bend, cut, mold, and machine, other steels. There are over 70 varieties and grades.

They are more expensive, more hardenable, better heat resistant, easier to heat treat, and more difficult to machine than carbon and alloy steels.

Prefix identification:

W – cold worked, water hardened – relatively inexpensive, susceptible to quench cracking

O – cold worked, oil hardened – do not distort during quenching, widely used tool steel.

A – cold worked, medium alloy air hardened – will air harden up to 6 inch thickness,

D – cold worked, high carbon and high chromium – D2 is the most widely used tool steel in the US. It has low quenching distortion, air harden up to 10 inch thickness, very abrasion resistant.

- S – shock resistant – used for impact applications such as chisels, has low abrasion resistance (not good for wear applications).
- H – hot worked – used for hot metal working
- M – high speed (molybdenum) – developed as cutting tools to machine other metals at high speed
- T – high speed (tungsten)
- P – used for molds, primarily in plastic injection molding
- L – special purpose – used in structural applications not as tooling.

Examples:

- M1 – Drills, saws, lathe and planer tools
- A2 – punches, embossing dies
- D2 – cutlery, drawing dies
- O1 – shear blades, cutting tools
- S1 – pipe cutters, concrete drills
- W1 – blacksmith tools, wood-working tools

MARAGING STEELS

Designation: ASTM A 538)

Maraging steels take their name from “martensitic age hardening”. They are high strength steels hardened by metallurgical reactions not involving carbon. They are strengthened by precipitation hardening of intermetallic compounds.

Properties:

- Very high strength (150-350ksi yield strength)
- Extremely high fracture toughness (100-240ksi-in^{1/2})
- Very weldable
- Susceptible to stress corrosion cracking in aqueous environments.

Applications: aircraft forgings, structural parts, bearings, shafts, bolts, punches, dies

NONFERROUS ALLOYS

Nonferrous alloys are alloys based on a metal other than iron. The most common are aluminum, titanium, and copper based alloys, but numerous other metals are also alloyed to create specific unique properties.

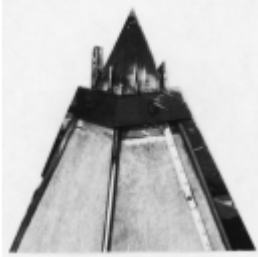
ALUMINUM ALLOYS

Aluminum alloys are widely used in various industries. Due largely to cost and low melting point, aluminum alloys are not as common as ferrous alloys. However, having 1/3 the density of iron and excellent corrosion properties, aluminum is used in many applications that steel simply would fail to function.

Although it is one of the most abundant element on earth, aluminum does not exist in metallic form naturally. It most commonly exists as bauxite, a form of aluminum oxide. Metallic aluminum was first produced in the laboratory in 1825 and became used commercially during World War II. Currently, there are over 600 specific alloys – way too many to become familiar with all of them.

One of the first engineering applications of aluminum was for the Washington Monument. During the construction, aluminum was selected as the capstone material (due to its good conductivity, it was believed that it would be a good lightning rod). Unlike copper, it would not oxidize and stain the masonry work. The aluminum cap weighed just over 1 pound, stood about 9 inches tall and was put in place in 1884 just prior to the opening dedication. The cost? A mere \$225. Quite expensive considering that the highest paid construction workers who built the monument were paid \$2 per day. It was comparably priced with silver.

(<http://www.tms.org/pubs/journals/JOM/9511/Binczewski-9511.html>)



General properties of aluminum alloys

- good thermal and electrical conductor
- ductile
- readily cast, machined, welded, formed
- does not experience ductile-to-brittle transition
- less dense than almost all other engineering metals (1/3 that of steel, 1/2 that of titanium) - but about 1/3 the stiffness of steel and 1/2 that of titanium
- good corrosion resistance in atmospheric environments
- can be alloyed to have high strength
- can be anodized or coated to have high surface hardness

Designation of *wrought aluminum alloys* (by the Aluminum Association) – the first digit of the four digit scheme indicates primary alloying elements.

Heat treatable wrought alloys (can be strengthened by precipitation heat treating):

- 2xxx – copper
- 4xxx – silicone
- 6xxx – magnesium and silicone
- 7xxx – zinc
- 8xxx – other elements

Non-heat treatable wrought alloys (cannot be precipitation hardened):

- 1xxx – commercially pure aluminum
- 3xxx – manganese
- 5xxx – magnesium

Cast aluminum alloys

Alloys specifically designed for casting have substantially different compositions than wrought alloys. As with wrought alloys, some cast alloys are heat treatable and others are not. They are designated as follows according to primary alloying elements:

- 1xx.x – 99.00% pure aluminum
- 2xx.x – copper
- 3xx.x – silicone with copper and/or magnesium
- 4xx.x – silicone
- 5xx.x – magnesium
- 7xx.x – zinc
- 8xx.x – tin
- 9xx.x – other elements

Elements are added for:

- Chromium: improves conductivity, refines grain structure.
- Copper: increases strength, improves high temperature properties, improves machineability.
- Iron: naturally occurring impurity in aluminum alloys, will increase strength and reduce hot cracking.
- Lead/bismuth: improves machineability
- Lithium: reduces density.
- Magnesium: improves strength by solid solution strengthening, with small amount of silicon will precipitation hardening if at least 3% magnesium, difficult to cast aluminum alloys with magnesium
- Manganese: used with iron to improve castability, improves ductility and impact strength
- Silicone: improves fluidity for casting and welding, reduces hot-cracking, improves corrosion resistance
- Titanium: grain refiner

Zinc: can be used with other elements to increase strength, but reduces castability

The four digit scheme is followed by a temper designation (a letter followed by one to three digit number):

- xxxx – F As fabricated. Applied to products shaped by cold working, not hot working. Also applied to castings which have no specific thermal treatment.
- xxxx – O Annealed. Applied to wrought products that have been annealed to their lowest strength. Applied to cast products that have been annealed to increase ductility and dimensional stability for subsequent machining.
- xxxx – W Solution heat-treated. This is applied to materials that naturally age over a period of days to years. Alloys in the W condition are not yet precipitation hardened. In order to maintain the W condition for extended time, the alloy may need to be stored at low temperature.
- xxxx – H Strain hardened. Wrought products that have been strain hardened (cold worked) to increase strength.
 - H1xy – strain hardened only, no subsequent heat treatment
 - H2xy – strain hardened and partially annealed
 - H3xy – Strain hardened and stabilized. Stabilizing improves ductility and eliminates age softening at room temperature. Is applied only to alloys that over age at room temperature.

The “x” indicates the degree of strain hardening:

- x=8 – fully hard (as hard as the alloy can become due to strain hardening)
- x=6 – three-quarters hard
- x=4 – half hard
- x=2 – quarter hard

The “y” indicates more subtle variations in properties than indicated by the “x”

- xxxx – T Thermally treated.
 - T1 – Cooled from hot working temperature and naturally aged
 - T2 – Cooled from hot working temperature, cold worked, naturally aged
 - T3 – Solution heat treated, cold worked, naturally aged
 - T4 – Solution heat treated, naturally aged
 - T5 – Cooled from elevated temperature and artificially aged. Applied to materials that are hot rolled (such as extrusions) or cast, then precipitation heat treated.
 - T6 – Solution heat treated and artificially aged.
 - T7 – Solution heat treated and overaged or stabilized. Applied to wrought products that have been intentionally overaged to improve corrosion resistance (especially stress corrosion cracking or exfoliation corrosion). Applied to cast products that are artificially aged to improve dimensional and strength stability.

- T8 – Solution heat treated, cold worked, artificially aged. Products that are cold worked in the “soft” solution heat treat condition to increase strength and then are artificially aged to further increase strength or to provide dimensional stability.
- T9 – Solution heat treated, artificially aged, cold worked. Applied to products that are cold worked to increase strength after aging.
- T10 – Cooled from elevated temperature, cold worked, artificially aged. Products that are shaped at elevated temperature (such as extrusions) are then cold worked to increase strength, and then artificially aged to further improve mechanical properties.
- The above temper designations are further refined. The “x” below refer to the above temper designations (1 through 10).
- Tx51 – cold rolled bars, plates, rods that are stress relieved by stretching
- Tx510 – extrusions that are stress relieved by stretching
- Tx511 – stress relieved by stretching, then straightened
- Tx52 – stress relieved by compression after solution heat treatment or after cooling from a hot working process
- Tx54 – die forgings that are stress relieved by restring old in the finish die.

Surface treatments of aluminum alloys

Anodizing – the electrochemical plating process applied to aluminum alloys to build up a relatively thick protective oxide layer (Al_2O_3). The oxide is very hard and protects from wear and improves corrosion. It may be colored to improve appearance. Alloys containing large amounts of copper (>3%) or silicone (>5%) do not anodize well.

Common alloys and their applications:

Wrought:

- 3003-H14 or O, pressure vessels, chemical equipment
- 5052-H34 or O, truck and marine uses, hydraulic tubes, fuel and air lines
- 2024-T6 or O, aircraft structures requiring good fracture toughness, truck wheels
- 6061-T6 or O, widely used general purpose alloy
- 7075-T6, aircraft structures requiring high strength

Cast:

- 295.0-T4, aircraft wheels, flywheels
- 356.0-T6, pump parts, transmission cases, axle housings, truck wheels
- 332.0-T5, automotive pistons
- 413.0, large intricate castings

TITANIUM ALLOYS

Titanium is an abundant earth element, but it is difficult to refine. Titanium is quite expensive, and since it is not widely used, the introduction of a single new product can result (through the law of supply and demand) in a substantial price increase. The cost of a titanium part can be between 5-20 times that of a comparable aluminum part. Aluminum parts are between 3-10 times comparable steel parts.

Titanium received its name in reference to the so-called elder gods in Greek mythology. The Titans ruled the earth before the Olympians overthrew them. As implied, titanium is a “formidable” material having high strength and toughness. It was first discovered in 1791 by the Reverend William Gregor. It was first purified in metal form in 1910 by Mathew Hunter. Commercial processes were developed in the 1940’s.

General properties

- high melting point (1671C, 3040F) – slightly higher than steel
- relatively low density (about 1.5 times that of aluminum, 1/2 of steel)
- modulus of elasticity of 18Mpsi (about twice that of aluminum, 1/2 of steel)
- relatively poor conductor
- difficult to machine
- can be welded in an inert environment
- excellent corrosion resistance at room temperature, but reactive at high temperature
- can be stronger than most steels (~ 200ksi yield strength)
- can have high fracture toughness (~60 ksi – in^{1/2})

Designation: ASTM B265 covers sheet, strip, and plates of common titanium alloys

Titanium alloys have three basic microstructures:

- α – single phase, HCP (least strong, most ductile of the alloys)
- β – single phase, BCC (high strength, but lower toughness)
- $\alpha - \beta$ – two phase (moderately high strength, good toughness)

Applications:

Ti-5Al-2.5Sn (5% aluminum, 2.5% tin) α -microstructure – gas turbine blades

Ti-6Al-4V (6% aluminum, 4% vanadium) α - β microstructure – high strength prosthetic implants, chemical processing equipment

Ti-6Al-6V-2Sn – α - β microstructure – high strength airframe parts, rocket engine casing

Ti-10V-2Fe-3Al – β microstructure – excellent combination of strength and toughness

ALLOYS OF:

copper, nickel, magnesium, beryllium, zinc, lead

While not widely used in machine design, each of these alloys have unique properties that may be indispensable for a specific application.

Copper

Copper is one of the oldest engineering metals. It has been used for millennia as cooking vessels and other applications where malleability was required to shape useful items.

Alloys and applications

Brass – copper + zinc

Cartridge brass – 30% zinc (radiator cores, ammunition components, lamp fixtures)

Leaded brass – copper, zinc, lead

Tin brass – copper, zinc, tin

Bronze – copper + tin or aluminum (bearings, bushings, piston rings)

Copper – nickel (condenser and heat exchanger components)

Nickel silvers – copper, nickel, zinc

Copper – beryllium (springs, firing pins, bushings)

Nickel

Nickel is used primarily as an alloying element in other alloys or for plating other alloys. Commercially pure nickel has good corrosion resistance and electrical conductivity. The most common nickel alloys are called *Monels* (nickel alloyed with copper). These have similar mechanical and corrosion properties to stainless steel but are better for welding. *Inconels* and *Incolloys* are nickel based superalloys (good at high temperature).

Magnesium

It is the third lightest engineering metal (lithium and beryllium are less dense). Applications of magnesium are mostly limited to low load applications requiring light weight. Pure magnesium is very weak (10ksi) and therefore is used only as an alloy. It has low ductility and low elastic modulus, but excellent machineability. Magnesium alloys have replaced many polymers in applications such as automotive and handheld devices. They are more easily recycled, stronger and stiffer, and less expensive than many polymers.

Beryllium

Beryllium alloys have two distinct selling points: they are very light weight and they transmit x-rays. They also have a high modulus of elasticity (42Mpsi). They are also quite expensive (10X titanium) and may be a health hazard in powder form.

Zinc

Zinc has a low melting point and is easily cast. Also, zinc and its alloys do not behave elastically, rather they creep at all stress levels and temperatures. The most advantageous application of zinc is as a plating over steel. It has excellent corrosion properties and is anodic with respect to steel (providing anodic protection).

Lead

Lead is not used as a structural material. However, it has the unique characteristic of high density in combination with low cost. Although most designs struggle to reduce weight, there are applications, such as counterbalancing, for which high density is desired. Due to its density, it is also relatively opaque to x-rays so it is often used as shielding.

REFRACTORY METALS:

Zirconium, niobium (a.k.a. columbium), tantalum, molybdenum, tungsten, rhenium
Refractory refers to excellent heat resistance. Refractory metals have melting points over 3000°F (1650°C). They owe their high melting points to very strong interatomic bonding. Strong bonding also results in very high elastic moduli, high hardness, and high strength. Even though they have superior high temperature capability, they are not widely used. Other less expensive and readily available materials are usually the preferred choice.

SUPERALLOYS

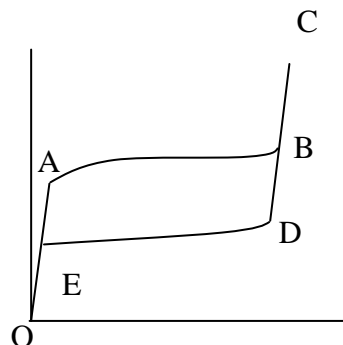
Superalloys have excellent combinations of properties. Specifically, they exhibit very high strength at high temperature and they have excellent corrosion resistance. The predominant metals in these alloys are cobalt, nickel or iron. They are often alloyed with refractory metals, titanium, and/or chromium. They find applications in gas turbines and similar high stress high temperature environments.

SHAPE MEMORY ALLOYS

Shape memory alloys (SMA) have two very unique characteristics: pseudo-elasticity and shape memory effect. These materials undergo phase transformations between austenite and martensite. These are not the traditional “austenite” and “martensite” discussed in basic ferrous metallurgy. In these materials, martensite exists at “low” temperature and is very formable. Austenite exists at higher temperature and is stronger. In most SMA’s the temperature difference between “low” and “high” is only about 10°C.

Pseudo-elasticity refers to the alloys ability at “high” temperature to be extremely flexible (above the 100% austenite transformation temperature). Mechanical loading transforms the austenite into flexible martensite. When the load is released, the martensite transforms back into austenite and retains its original shape. The alloys is almost like rubber.

Pseudo-elastic stress-strain curve
(Load path O-A-B-C-D-E-O):



The shape memory effect refers to the materials ability to return to its original shape upon heating. This is accomplished by deforming the material at low temperature (below the 100% martensitic transformation temperature). The soft martensite plastically deforms by twinning. However, upon heating to cause transformation to austenite, the material returns to its original shape and size.

These have applications as vascular stints, thermostats, eyeglass frames, and orthodontia.

AMORPHOUS METALS

Metals by their very nature form crystalline solids. However, if quickly cooled from the molten state it is possible to form non-crystalline, a.k.a. amorphous, metals. These are also sometimes referred to as glassy metals. Cooling must be so fast as to prevent even local diffusion from occurring otherwise crystals would form. Due to the high cooling rates required, the thickness of parts is limited to less than about a centimeter. These alloys can have high modulus of elasticity, high strength, and extremely high elastic strain limit. The elastic strain limit is the amount of strain the material can experience and still return to its original shape. They have found limited applications in the sporting goods industry (golf).

CERAMICS

Ceramics consist of metallic and nonmetallic materials bonded with ionic and/or covalent bonds. They may be crystalline or amorphous. Ceramics from antiquity (glass, bricks, tiles) still have engineering applications; however, engineering ceramics are typically compounds such as aluminum oxide (Al_2O_3).

General properties:

- high strength (especially compressive)
- high hardness and wear resistance
- high stiffness
- low density
- low conductivity
- low thermal expansion
- excellent high temperature stability
- excellent chemical stability (not susceptible to chemical attack)
- low toughness

Carbon

Carbon has four basic allotropes with potential applications. These may be considered to be ceramics:

Graphite (from Greek meaning *write*) is highly anisotropic, is a good thermal and electrical conductor, effective lubricant, very strong and stiff, low density, high thermal stability

Diamond is the hardest, stiffest and least compressible naturally occurring material. Diamonds are used to coat cutting tools to enhance their life.

Buckyballs are spherical clusters of carbon (C_{30} to C_{100}). They take their name from the geodesic truss form they create which was developed by the architect Buckminster Fuller (they are also referred to as *fullerenes*). They have no current industrial applications.

Carbon Nanotubes tubes of indefinite length are formed from carbon forming similar hexagonal truss work to graphite. They are extremely strong and stiff, ($E=1.2 \times 10^{12}$ Pa, 5 times greater than steel). Applications include being used as fibers in composites.

POLYMERS

There are three basic groups of polymers: thermosetting, thermoplastic, and elastomers. Polymers are made from long covalently bonded chains with carbon typically as the backbone. They are generally less expensive than most other materials, have relatively low operating temperatures, low stiffness and strength, and they are poor conductors.

Thermoplastics

Thermoplastic polymers will soften and melt upon heating. As such, thermoplastic parts are frequently produced using inexpensive injection molding processes. The majority of plastic parts are made from thermoplastic polymers.

Thermoplastics typically consist of long, 1-dimensional polymer chains. Upon heating, the secondary bonds between chains weaken and the material loses strength and stiffness.

General properties of thermoplastic

- high chemical stability (although specific environments can cause significant degradation of specific thermoplastics)
- non-linear stress-strain relation. They exhibit viscoelastic behavior and are highly susceptible to creep.
- stress-strain properties are highly dependent upon temperature and rate
 - o high strain rates increase stiffness and strength, but decrease ductility
 - o high temperatures decrease stiffness and strength
 - o low temperature decreases toughness and ductility
- low operating temperature (<50-200°F)

Materials and applications

ABS - excellent strength and toughness (toys, casings, etc.)

Acrylic – (transparent, does not weather, brittle) lenses, transparent enclosures

Teflon (PTFE) – (chemically inert, low coefficient of friction, may be used up to 500°F) chemical pipes and valves, anti-adhesive coatings, high temperature electronic parts

Nylon – (good strength, abrasion resistant, low friction coefficient) bearings, gears, cams, bushings, handles

Polycarbonate – (transparent, impact resistant) safety helmets, safety glasses, light globes

Polyethylene – (high chemical resistance, tough, poor resistance to weathering) flexible bottles, toys, ice trays

UHMW Polyethylene – (very low friction coefficient, abrasion resistant) bearings, wear plates (high toughness, good lubrication and wear characteristics)

Polypropylene (chemically inert, good fatigue resistance, poor UV resistance)– sterilizable bottles, cabinets

Thermosetting

Thermosetting polymers are different than thermoplastic – they do not melt upon heating (but they will char). They become solid by polymerization processes. Short polymers are joined together to make large, interconnected, 3-dimensional networked “chains”. The polymerization may be caused by UV exposure, heat, or a number of other catalytic mechanisms. The 3-dimensional network structure increases the operating temperature that these materials can withstand. It also decreases their sensitivity to changes in temperature. Since they do not melt, parts cannot be made through a casting process.

General properties of thermosetting polymers

- typically harder, stronger, and more brittle than thermoplastics

- better dimensional stability than thermoplastics
- higher operating temperatures (some up to about 300°F)
- less viscoelastic, less susceptible to creep

Materials and applications

Epoxies – electrical moldings, protective coatings, used in composite materials

Phenolics – motor housings, telephones, electrical fixtures

Polyesters – helmets, fiberglass, auto body components, chairs.

Elastomers

Elastomers exhibit highly non-linear elasticity. They can experience large amounts of strain without breaking and without taking on permanent deformation. Rubber bands are made from elastomers.

Materials and applications

Natural rubber – shoe soles, gaskets, tires

Nitrile – gasoline and oil – hoses, seals, and o-rings

Neoprene – chemical tank linings, belts, hoses, seals, gaskets

COMPOSITES

Composites are materials composed of two or more *distinct* materials that are combined to improve properties. The materials are *distinct* in that there is a macroscopic interface between them. Engineering alloys are not considered to be composites; even alloys consisting of second phase particles. The second phase particles are typically microscopic. Since “micro vs. macro” may not always hold true, a better definition may entail how the two distinct materials are combined. In an alloy, they are produced through metallurgical processes. In a composite, they are usually mechanically combined with at least one of the materials being in solid phase during the “combining” process.

Natural composites consist of wood, bone, and concrete (portland cement). Although some mechanical engineers are involved with orthopedic devices and a working knowledge of bone is essential, it is not an engineering material. Engineered composites are classified by their matrix material. The matrix material in a composite surrounds the filler material. Matrix material may be metal or alloys, ceramics or polymers. The filler’s job is to improve the properties of the matrix. Filler is usually very small diameter continuous fibers, short fibers, or particulate.

Metal Matrix Composites (MMC)

Metal matrix composites are often made from aluminum alloys with hard ceramic fibers or “whiskers” (such as SiC). The filler material typically increases strength and stiffness of the matrix and may reduce creep. The filler is either continuous fiber, short fiber, or particulates (whiskers). Due to the added complexity of manufacturing MMC’s over alloys, the improved properties often do not justify their use. They are used in specialty

applications where small improvements are significant: sporting goods, limited use in aerospace and automotive.

Ceramic Matrix Composites (CMC)

Adding short fibers or whisker to ceramics can increase their tensile strength and toughness significantly. Nonetheless, they are not widely used.

One composite that is used at very high temperature is graphite-graphite composite. It is manufactured similarly to polymer composites. Sheets of continuous graphite fibers are impregnated with a polymer resin. The sheets are then “pyrolyzed” – heated to drive off the oxygen, nitrogen, etc., leaving behind a graphite matrix. These can be used for rocket engine nozzles, and operate at up to 3600°F.

Fiber Reinforced Plastic.

By far the most widely used engineered composite material are fiber reinforced polymers. These composites have much higher stiffness, strength and toughness than the matrix material alone.

The two most common such composites are “fiberglass” and “graphite.” Fiberglass typically consists of chopped glass fibers embedded in an epoxy and sprayed over a mold to create a desired shape. Alternatively, woven mats of continuous glass fibers may be formed over a mold and epoxy applied to the mat. These composite materials are light weight, but strong and tough. They are used widely for such applications as shower and bathtub stalls, auto body panels, and fishing poles.

The term “graphite” is virtually synonymous with “composite.” A more appropriate name for these composites is graphite epoxy. These composites are usually composed of continuous graphite fibers embedded in an epoxy resin. So called “prepreg” (pre-impregnated) are sheets consisting of unidirectional or woven fibers of graphite that have been embedded in an uncured epoxy resin. These sheets are sticky and may be layered together over a mold to build up a structure. Often a nearly hollow honeycomb or foam core is used to provide thick sections without adding much weight. The built up prepreg layers are then placed in a furnace or autoclave at around 200-350°F to cure the epoxy. Very strong, stiff, tough, light weight parts with extremely complex geometry may be produced. Applications include aerospace, automotive and sporting goods – anywhere spending large sums of money to produce strong light weight parts is justified.

The negative side to graphite epoxy composites is their susceptibility to nearly invisible impact damage and their high cost. They also are unsuitable for temperature exposure above about 300°F.

SURFACE ENGINEERING

Since the surface of the material must interact with the world around it, it plays a special role in engineering materials. The surface plays a pivotal role in corrosion protection, wear applications and fatigue initiation. As such, much work has been invested in developing methods to improve surface properties. There are three general categories: surfaces that coat the bulk material (for example, paint); treatments that penetrate and alter the near surface properties of the material itself; and the surface finish of the material.

Surface Finish

The surface finish of the material plays a key role in fatigue and potentially a role in corrosion as well. A very fine, smooth finish can substantially delay the onset of fatigue initiation. Rough surfaces not only provide fatigue crack initiation sites but a rough surface has more surface energy, and hence they are more chemically active. Additionally, they attract and retain moisture compounding the issue.

Platings and Coatings

Platings and coatings are applied over the surface of the bulk material. These can provide a barrier to corrosion and/or provide improved interface contact properties to prevent wear and galling.

Examples: thin film coatings, thermal spray, paints, anodized aluminum, plating (such as zinc on steel), and lubricants.

Surface Treatments

Surface treatments modify the near surface characteristics of the bulk material. These may increase compressive residual stress (a good thing for increasing fatigue life and stress corrosion cracking resistance), increase hardness (improve wear life) or decrease chemical reactivity (decrease corrosion rate).

Examples

Mechanical deformation to improve residual stress: shot peening, vibration, cold worked holes.

Diffusion treatments to increase hardness and in some cases introduce compressive residual stress: carburizing, nitriding, carbonitriding, ferritic-nitrocarburizing.

Selective surface hardening: flame, induction, laser, electron beam.

High energy treatments: Ion implantation, laser glazing, laser fusion.