PROCESSING AND APPLICATIONS OF MATERIALS

When making a new device/component, most often we come across a very familiar problem-selection of fit for purpose materials. Selection of materials play very important role in preventing failures. Some of the important factors governing selection are: strength, ease of forming, resistance to environmental degradation, etc.

Materials are broadly divided into metals/alloys, plastics and ceramics.

Metals/Alloys

- Metallic materials are broadly of two kinds – ferrous and non-ferrous materials. Ferrous materials are those in which iron (Fe) is the principal component. All other materials are categorized as non-ferrous materials. Other classification is based on their formability. If materials are hard to form, components with these materials are fabricated by casting, thus they are called cast alloys. If material can be deformed, they are known as wrought alloys. Thus metallic materials are usually strengthened by two methods – cold work and heat treatment.

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- Strengthening by heat treatment involves specific heat treating procedure. When a material can not be strengthened by heat treatment, it is referred as non-heat-treatable alloys.

Ferrous materials

- Ferrous materials are popular because of abundant raw materials i.e. iron ore combined with economical extraction, ease of forming and their versatile mechanical and physical properties. Their disadvantages are their poor corrosion resistance, relatively high density and comparatively low electrical and thermal conductivities.
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- In ferrous materials the main alloying element is carbon (C) and are thus classified as when the carbon content is either less/higher than 2.14%. The ferrous alloys with less than 2.14% C are termed as steels and the ferrous alloys with higher than 2.14% C are termed as cast irons.

Steels

- In steels, carbon is present in atomic form at interstitial sites of Fe microstructure. Alloying additions are to improve properties, corrosion resistance, etc.

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- Mechanical properties of steels are very sensitive to carbon content. Hence, we classify steels based on their carbon content. Steels are basically three kinds: low-carbon steels(% wt of C<0.3), medium carbon steels(0.3 <% wt of C < 0.6)and high-carbon steels (% wt of C > 0.6).We can also classify steels by amount of alloying additions, and based on this steels can either be (plain) carbon steels or alloy-steels. Low carbon steels are produced in the greatest quantities than other alloys. Carbon present in these alloys is limited, and is only enough to be strengthened by cold work.

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- These alloys are relatively soft, ductile and have high toughness. They are easily machineable and weldable. Typical applications of these alloys include: structural shapes, tin cans, automobile body components, buildings, etc.
- A special group of ferrous alloys with noticeable amount of alloying additions are known as HSLA (high-strength low-alloy) steels. Common alloying elements are: Cu, V, Ni, W, Cr, Mo, etc. These alloys can be strengthened by heat treatment. They are ductile and formable. Typical applications of these HSLA steels are as support columns, bridges, pressure vessels.

- Medium carbon steels: Stronger than low carbon steels and are less ductile than low carbon steels. They can be heat treated to improve their strength. They are often used in tempered condition. Ni, Cr and Mo alloying additions improve their hardenability. Typical applications include: railway tracks & wheels, gears, other machine parts which may require good combination of strength and toughness.
- High carbon steels: They are the strongest and hardest of carbon steels. Their ductility is very limited and are heat treatable, and mostly used in hardened and tempered conditions.

- They possess very high wear resistance, and capable of holding sharp edges. They are used for tool application such as knives, razors, hacksaw blades, etc. With addition of alloying element like Cr, V, Mo, W which forms hard carbides by reacting with carbon present, wear resistance of high carbon steels can be improved considerably.
- Stainless steels: The name comes from their high resistance to corrosion i.e. they are rust-less (stain-less). Steels are made highly corrosion resistant by addition of special alloying elements, especially a minimum of 12% Cr along with Ni and Mo.

- Stainless steels are mainly three kinds: ferritic & hardenable Cr steels, austenitic and precipitation hardenable (martensitic, semi-austenitic) steels. This classification is based on prominent constituent of the microstructure. Typical applications include cutlery, razor blades, surgical knives, etc.
- Ferritic stainless steels are principally Fe-Cr-Calloys with 12-14% Cr. They also contain small additions of Mo, V, Nb, and Ni. Austenitic stainless steels usually contain 18%Cr and 8% Ni in addition to other minor alloying elements. Ni stabilizes the austenitic phase assisted by C and N.

- Other alloying additions include Ti, Nb, Mo (prevent weld decay), Mn and Cu (helps in stabilizing austenite). By alloying additions, for martensitic steels Ms is made to be above the room temperature. These alloys are heat treatable. Major alloying elements are: Cr, Mn and Mo. Ferritic and austenitic steels are hardened and strengthened by cold work because they are not heat treatable. On the other hand martensitic steels are heat treatable. Austenitic steels are most corrosion resistant, and they are produced in large quantities. Austenitic steels are non-magnetic as against ferritic and martensitic steels, which are magnetic.

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- Cast irons :Commercially cast irons contain about 3.0-4.5%C along with some alloying additions. They melt at lower temperatures than steels i.e. they are responsive to casting. Casting is the most used fabrication technique for these alloys. Hard and brittle constituent present in these alloys; cementite is a meta-stable phase, and can readily decompose to form α-ferrite and graphite. The tendency of cast irons to form graphite is usually controlled by their composition and cooling rate. Cast irons are categorized as gray, white, nodular and malleable cast irons based on the form of C present.

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- Gray cast iron: It consists of carbon in the form of graphite flakes, which are surrounded by either ferrite or pearlite. Fractured surface of these alloys look greyish hence the name. Addition of Si (1-3wt.%) is responsible for decomposition of cementite, and also high fluidity. Thus castings of intricate shapes can be easily made. Due to graphite flakes, gray cast irons are weak and brittle. However they possess good damping properties, and thus typical applications include: base structures, bed for heavy machines, etc. they also show high resistance to wear.

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- White cast iron: When Si content is low (< 1%) in combination with faster cooling rates, there is no time left for cementite to get decomposed, thus most of the brittle cementite remains. Because of presence of cementite, fractured surface appear white, hence the name. They are very brittle and extremely difficult to machine. Hence their use is limited to wear resistant applications such as rollers in rolling mills. Usually white cast iron is heat treated to produce malleable iron.
- Nodular (or ductile) cast iron: Alloying additions are of prime importance in producing these materials

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- Small additions of Mg / Ce to the gray cast iron melt before casting can result in graphite to form nodules or sphere-like particles. Matrix surrounding these particles can be either ferrite or pearlite depending on the heat treatment.They are stronger and more ductile than gray cast irons. Typical applications include: pump bodies, crank shafts, automotive components, etc. Malleable cast iron: These are formed after heat treating white cast iron. Heat treatments involve heating the material up to 800-900 C, and keep it for long hours, before cooling it to room temperature. High temperature incubation causes cementite to decompose and form ferrite and graphite. Thus these materials are stronger with appreciable amount of ductility. Typical applications include: railroad, connecting rods, marine and other heavy-duty services.

Non-ferrous materials

- The specific advantages non-ferrous materials have over ferrous materials include ease of fabrication, high relatively low density, and high electrical and thermal conductivities.
- Aluminium alloys: These are characterized by low density, high thermal & electrical conductivities, and good corrosion resistant. They are ductile even at low temperatures and can be formed easily. A great limitation is their low melting point (660C), which restricts their use at elevated temperatures. Can be strengthened by both cold and heat treatment.

- Al alloys can be designated into two groups, cast and wrought. Chief alloying elements are Cu, Si, Mn, Mg, Zn. Recently, alloys of Al and other low-density metals like Li, Mg, Ti gained much attention as there is much concern about vehicle weight reduction. Al-Li alloys enjoy much more attention especially as they are very useful in aircraft and aerospace industries.
- Common applications include beverage cans, automotive parts, bus bodies, aircraft structures, etc.

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- Copper alloys: include bronze which has been used for thousands of years. It is an alloy of Cu and Sn. Cu is soft and ductile thus hard to machine, and has virtually unlimited capacity for cold work. One special feature of most of these alloys is their corrosion resistant in diverse atmospheres. Most of these alloys are strengthened by either cold work or solid solution method. Common Cu alloys include Brass, alloys of Cu and Zn (e.g.: yellow brass, catridge brass, muntz metal, gilding metal); Bronze, alloys of Cu and other alloying additions like Sn, Al, Si and Ni.

- Bronzes are stronger and more corrosion resistant than brasses. Also are Beryllium coppers which possess a combination of relatively high strength, excellent electrical and corrosion properties, wear resistance, can be cast, hot worked and cold worked. Cu alloys are used for costume jewellery, coins, musical instruments, electronics, springs, bushes, surgical and dental instruments, radiators, etc.

Magnesium alloys: have low density among all structural metals. Mg alloys are difficult to form at room temperatures and so are usually fabricated by casting or hot working.

Mg alloys are characterised as either cast or wrought type, and some of them are heat treatable. Major alloying additions include Al, Zn, Mn and rare earths. Mg alloys are commonly used for hand-held devices like saws, tools, automotive parts like steering wheels, seat frames, electronics' casing for laptops, camcoders, cell phones etc.

Ti and its alloys: are of relatively low density, high strength and have very high melting points. They are easy to machine and forge. However the major limitation is Ti's chemical reactivity at high temperatures, which necessitated special techniques to extract.

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- Thus these alloys are expensive. They also possess excellent corrosion resistance in diverse atmospheres, and wear properties. Common applications include: space vehicles, airplane structures, surgical implants, and petroleum & chemical industries.

Refractory metals: are metals of very high melting points. For example: Nb, Mo, W and Ta. They also possess high strength and high elastic modulus. Common applications include: space vehicles, x-ray tubes, welding electrodes, and where there is a need for corrosion resistance.

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- Noble metals: These are eight all together and are, Ag, Au, Pt, Pa, Rh, Ru, Ir and Os. All these possess some common properties such as: expensive, soft and ductile, oxidation resistant.
- Ag, Au and Pt are used extensively in jewelry, alloys are Ag and Au are employed as dental restoration materials; Pt is used in chemical reactions as a catalyst and in thermo couples.

Processing/Fabrication of metals

- Metals/alloys are fabricated by different means to achieve metal/alloy objects of desired characteristics. There been many kinds of fabrication techniques, the choice of which depends on the properties of metal, product shape-size-properties, cost, etc. Fabrication techniques are of four types:
- Casting - to give a shape by pouring in liquid metal into a mould that holds the required shape, and allow the metal to harden without external pressure.
- Forming – to give shape in solid state by applying pressure. Machining – in which material is removed in order to give it the required shape.
- Joining – where different parts are joined by various means.
- Powder metallurgy is another useful technique.

- Casting: Usually employed when (a) product is large and/or has a complicated shape (b) particular material is low in ductility. It is usually economical compared with other techniques. Casting techniques are sand, die, investment and continuous casting.

Sand casting: Sand is used as casting material. A two piece mould (cope and drag) is formed by compact packing of sand around a pattern of required shape. Gating is provided for proper distribution of liquid metal.

Die casting: Here metal is forced into a mould by external pressure at high velocities. Usually a permanent two-piece mould made of steel is used. In this technique rapid cooling rates are achieved, thus it is inexpensive.

- Investment casting: In this, pattern is made of wax. Then fluid slurry of casting material is poured over which eventually hardens and holds the required shape. Pattern material is heated to leave behind the cavity. This technique is employed when reproduction of fine details, and an excellent finish are required. Example: jewellery, dental crowns, and gas turbine blades as well as jet engine impellers.
- Continuous casting: After refining, metals are usually in molten state, which are later solidified into ingots for further processing like forming. In continuous casting, solidification and primary forming processes are combined, where refined metal is cast directly into a continuous strand which is cooled by water jets.

- Metal forming: Common forming techniques are: forging, rolling, extrusion, and drawing. In these techniques, a metallic piece is subjected to external pressures (in excess of yield strength of the material which induces deformation and the material acquires a desired shape. There are basically two types – one that is performed at relatively low temperatures, cold working; and the other performed at relatively high temperatures, hot working. With hot working change in cross section occurs without material getting strengthened, while during cold working, fine details are achieved along with material getting strengthened.

Forging: involves deforming a single piece of metal, usually, by successive blows or continuous squeezing. In open die forging, two dies having the same shape are employed, usually, over large work-pieces; while in closed die forging, there may be more than two pieces of die put together having finished shape. Forged products have very good mechanical properties. Typical products include: crane hooks, wrenches, crank shafts, connecting rods.

Rolling: the most widely used forming technique because of high production rate and close dimensional control of final product.

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- It involves passing a piece of metal between two rotating rolls. Deformation is in terms of reduction in thickness resulting from applied compressive forces. This technique is typically employed to produce sheets, strips, foil rails, etc.

Extrusion: a technique which involves forcing a piece of material through a die orifice by compressive force. Final product from die will have the desired shape and reduced cross sectional area, and with constant cross-section over very long lengths. Two varieties of extrusion are, direct extrusion and indirect extrusion. Typical extrusion products are: rods, (seamless) tubes, utensils for domestic use.

Drawing: is pulling of material through die orifice using tensile forces. Reduction in cross-section results with corresponding change in length. Typical drawing strand has number of dies in a series. Rods, wire and tubes are commonly produced using drawing technique.

Machining: technique employs removal of metal from selected areas of a work piece to give final shape to the product. This contrasts with metal forming where metal is moved and volume is conserved. Machining is employed to produce shapes with high dimensional tolerance, good surface finish, and often with complex geometry.