Basics of Mechanical Engineering-1

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Lecture 22

Materials, Metals and Composites (Part 1 of 2)

This lecture is going to be very interesting. We are going to talk about different Materials. As you all know, materials will be classified as metals, polymers, ceramics and of course, today we have composites also coming into existence. The understanding whatever you have made in the course till now, it all gets converted into a product when you start understanding the material. Till now, we were looking into the characterization or specification or the loading patterns which is during service condition which comes on a material.

As I told you in the last lecture design is one phase plus material selection is also a very important parameter. So, we will try to cover Materials in this lecture.

Contents

- Introduction
- Metal
- Composites
- Glass
- Diamonds
- Case Study
- To Recapitulate

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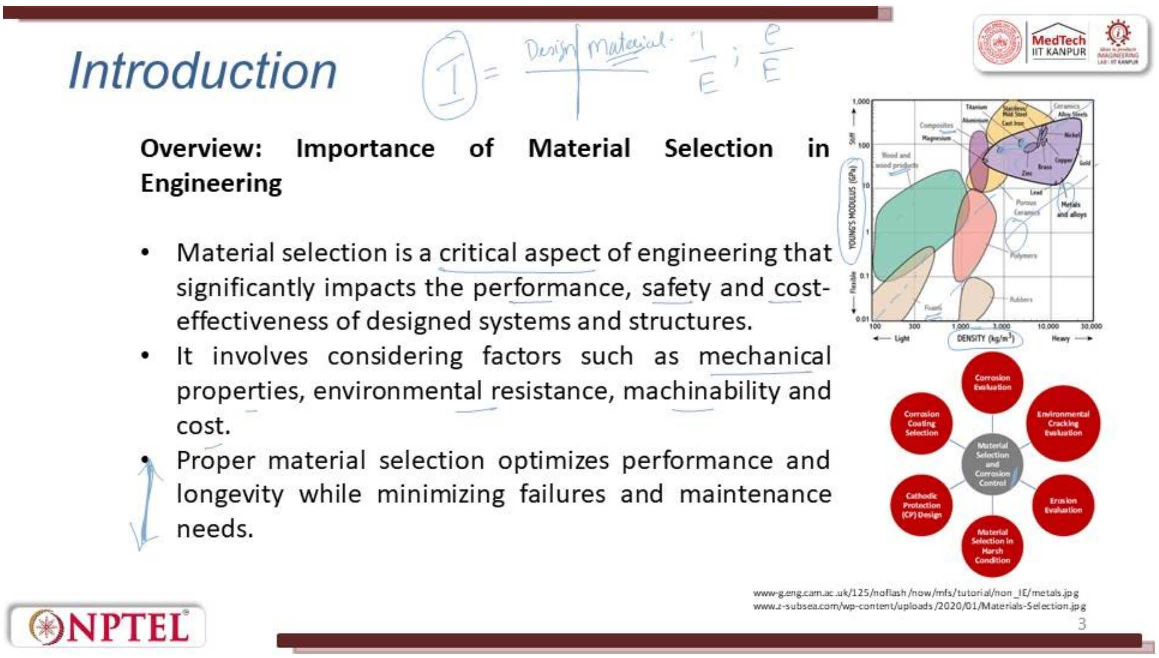
The lecture will have an introduction, then we will try to look at metals, then composites. Ceramics which I said is glass, diamond, few case studies and finally we will have a recap.



The overview and the Importance of Material Selection in Engineering. When you look at a graph like this, this graph is called as Ashby's curve. The interesting part of this graph is he takes different material properties and compares it with the strength. Certain graphs will have Young's modulus, yield stress, ultimate tensile, fracture, cost as against density. Some graphs will have Young's modulus and ultimate tensile strength. So here what he has done is he has taken a mixed bag and then he has compared material properties with the primary material characteristics.

For example, you can have in the x-axis thermal conductivity, electrical conductivity. You can have volume. You can have mass. So that is converted into density. Then you can have corrosion behavior.

So all these things, the physical parameters, hardness with respect to Young's modulus. You can have all combinations. With this combination, what he has done is, in his graph, he has placed almost a spectrum of materials. If you look at it, he has placed here wood and wood products. Here he has placed composites.

At some place, density very high, he has placed metals. You can see here. So these are sometimes Cast Iron products. Titanium falls here. Magnesium falls here.

So if you see here, magnesium is lighter or the density is lighter, lesser than titanium. In that case, magnesium should be popularly used for various moving parts which is coming into existence. For example, aeroplane, automobile. Now we are trying to look at magnesium. Then titanium.

Titanium is also lighter than compared to metals. That means to say iron materials, mild steel, stainless steel. It is lesser in density. So now we are trying to explore these possibilities. Looking into application for example with respect to Young's modulus, you see there is not much of compromise you do if you choose a titanium as against magnesium.

Now you have to take a call whether which one is good keeping cost that is primary. Second thing is you will see the longevity of the part. Third one if you see when you talk about all this moving let it be car, let it be plane, we always look at what is the mileage. So, if you are looking for mileage, magnesium will be chosen as against titanium. So, in this Ashby curve, he has plotted several spectrum of materials.

See, you see here foam. Foam has very low density, very low Young's modulus. So, it can be used for packing material. Then, if you move further down, you see here rubber. Rubber has very poor Young's modulus or very low Young's modulus and density is also, it is compromised, it is also low as compared to that of steel.

So, now look at applications. For example, sensor applications. Look at air bag. It is made out of elastomers. Right. So now with this graph, you get more and more and more understanding.

And as I told you in the beginning of the lecture, if you have any characteristics, for example, like modulus, you want to find out the modulus. So modulus of a I beam will have certain parameters which are called as Design parameters, certain parameters will have Material parameters. Leaving the design parameter, for example, we were discussing in few lectures about columns, then slender ratio. So, those things are Design parameters. The other thing is Material parameters.

In material parameters also, many a times you will have 1 by E or you will have something rho by E. So these are all, in the formula you can see for I channel or I beam, how do you calculate moment of inertia? So, their material properties whatever is there can be extracted from this curve. For example, density versus E in the formula if it comes. So, from this graph you can get. And now we can also try to figure out whether it has a relationship of 1, a relationship less than 1, greater than 1.

So now all you have to do is make slopes. From this slope, what all materials falls along this slope, you will choose those materials to meet out to your requirements. Now you see selection of material is very important. So importance of material selection in engineering. Material selection is a critical aspect of engineering that significantly impacts the performance, safety, cost effectiveness of the design system and structure.

It involves considering factors such as mechanical properties, environmental resistance, machinability and cost. If your E is very high, Young's modulus is very high, one part of interpretation is it should be a ceramic material. So ceramic material, machinability is a challenge. So all these things. So you can also have x-axis on machinability with respect to density, with respect to Young's modulus.

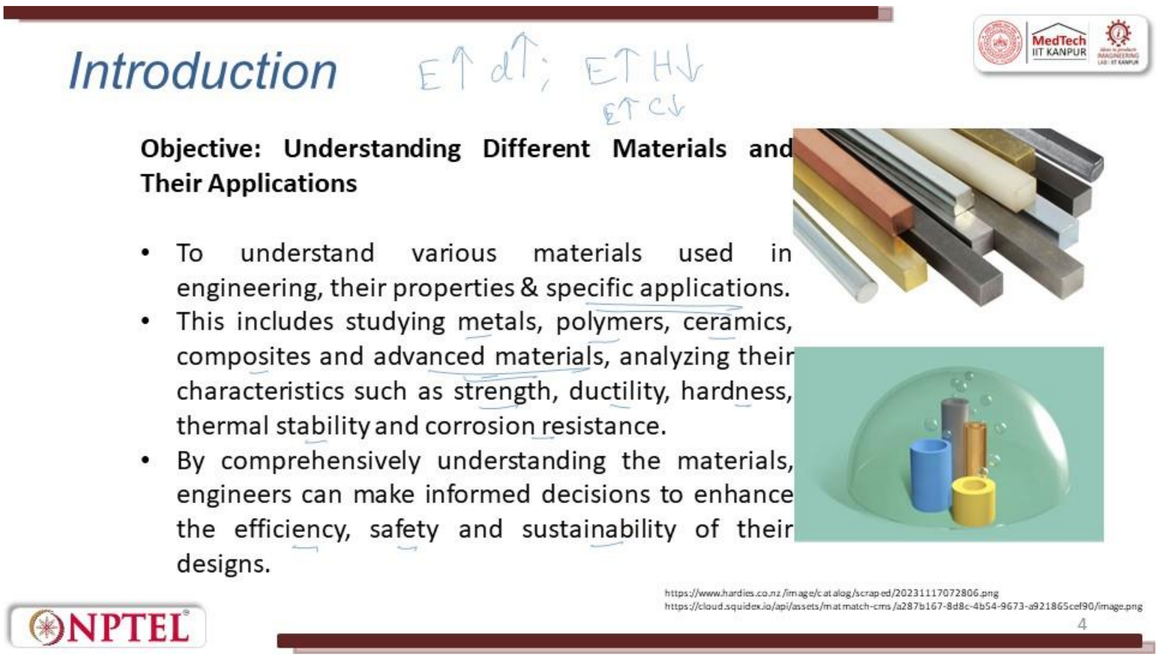
You can also have costability, malleability with respect to cost, with respect to density. All these parameters you will have. A proper selection, material selection optimizes performance and longevity while minimizing failure and maintenance needed. So this is where selection of materials is very important. When you look into this graph or this schematic diagram, whatever is there, so you can see here the material selection and corrosion control.

So this is you have to choose a material which has corrosion control or corrosion resistance behavior. For example, if you are staying along the beach and if you have a car, the choice of material selection for your silencer car body is very important as compared to that of the inland locations. Why? Because you have lot of corrosionness happening along the beach.

Even the reinforcement which is given for the buildings, what they do is the steel will be coated with polymer or they will try to protect it from the corrosive behavior. So when we are trying to choose material for corrosion control, you will see corrosion evaluation has to be done, then environmental cracking evaluation has to be done, erosion evaluation has to be done, material selection in harsh conditions. And then cathodic protection design will be there. Corrosion coating selection should be there. So all these things influence the corrosion control.

Suppose you take a ship which sails through in water for a long time. So they will always have a corrosion behavior. You cannot have a material which is non-corrosive. But they will always try to counter it or they will try to mitigate it in reducing it. So how do they do it?

They try to have cathodic production. They try to do proper coating also. For example, painting, which is polymer mixed, all these things they try. So all these factors are keeping only corrosion. These conditions will be looked forward to choose a proper material.



So, Understanding Different Materials and Their Application. To understand various materials used in engineering, their properties and specific applications are to be understood. As far as engineering is concerned, we start with specific application or we talk about service condition. I am trying to make a product which has to withstand this service condition. For example, when you try to make a toy which is given to kids. The most important parameter should be it has to be light in weight.

Second thing, it has to have a huge impact resistance. The third one should be it should not be toxic in nature because the kid will always try to put it in his mouth. When it is annoyed, it will throw or when it wants to have fun, it will throw. It has to be as light as possible because if it is made heavy, then the child will not have a habit of even touching the toy or picking the toy. They will play very nicely with balloons.

Why? Because balloon's density is very low. And it can be given multiple shapes and it has multiple colors. So this makes it interesting. So when you are trying to make a choice of material for a toy, you have to first understand what is its application and then come back and look at the properties.

This includes studying about metals, polymers, ceramics and composites. And of course, today you have advanced materials or exotic materials. So, we also try to study more and more about it. Because today what is happening? We need multiple combinations of properties for a material which are contradictory.

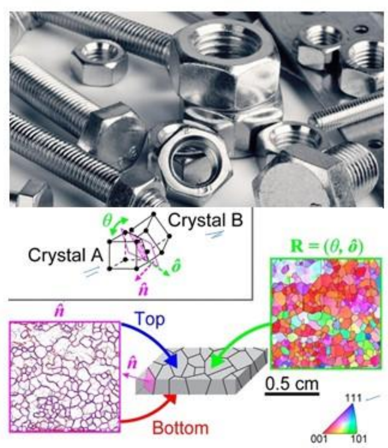
For example, we need a very high E value, Young's modulus value. Ductility also we need very high. We need a material which is having very high stiffness but very low hardness and it has to be designed for failure. So E is higher, H is smaller. You can have E very high and cost very low.

So now you see all combinations are coming into existence. So when it has to come into existence, we are looking at advanced materials wherein which a combination of metals and ceramics are tried. Analyzing their characteristics such as strength, ductility, hardness, thermal conductivity, corrosion resistance are major characteristics which are to be evaluated. By comprehensively understanding the material, engineers can make informed decisions to enhance the efficiency, safety and sustainability of the products.

Metals

Definition: Characteristics of Metals

- Metals are materials characterized by their ability to conduct electricity and heat, malleability, ductility, and typically high density. corrosion resistance.
- They possess a crystalline structure and exhibit a metallic luster.
- Metals are generally strong, durable, and have high melting points, making them ideal for a wide range of engineering applications.



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Characteristics of Metals are materials characterized by their ability to conduct electricity and heat apart from malleability, ductility and typically high density.

These are few characteristics. Corrosion resistance is also there. And when you look at section of metal, look the metal under a microscope, they possess a crystalline structure and exhibits a metallic luster. They are strong, durable and have very high melting point as compared to that of polymers, making them ideal for a wide range of applications. Initially, many of the parts in car were made out of metals, for example, bumper.

The front portion of the car, wherein which the car can be protected when it comes in contact with the front going car. The bumper was initially made out of metal. Today it is made out of polymer. Now majority of the metal parts are getting replaced by polymer. Chairs are getting replaced by polymer.

Stand, chair, plates, tumblers, laptop body, cell phone body, they are all getting converted into polymers today. Because it is cost effective and it is easy to make. When you look at a metal, it always exhibits a crystal structure or crystallinity is there. It is predominantly polycrystalline materials. So, when you try to take a section, you always will see there is a grain and a grain boundary.

So, you take a material, you section the material, you see here how does it look like. The plane this is a plane. So, you see the plane here and then you take another grain and look at it using high tech devices. So, today we have several electron microscopes which have come into existence where in which you can it also tries to talk about the plane orientation and here you see the grain structure. So, you can see when two materials are mixed are polycrystalline metal will have crystalline A and crystalline B.

So generally metals exhibit a polycrystalline behavior and this polycrystalline behavior tries to bring in lot of advantage or lot of characteristic features or properties for the metals. When we talk about metals, there is a spectrum of materials which are available. No pure metal is good for engineering application. We always look for an alloy because in pure metal you will have no defects. If there are no defects, then it becomes very difficult for you to deform.

So, we always try to use an alloyed material. What is the alloying? It is left to your choice depending upon the service condition and then the percentage is chosen, then it is mixed to get the required strength applications or to meeting out to your requirements.

The most commonly used in automobile industry, aerospace industry is aluminium. Wherever there is a structural load, we go for steel, iron.

Wherever there is a temperature dependent phenomena dominating, heat dependent temperature/heat phenomena dominating, we always go for copper. So electrical conductivity and thermal conductivity, if there is an application, we always go for copper. So copper is used in almost all the heat exchangers. Heat exchangers are where in which there is a transfer of heat between two media. So copper.

Then advanced version of copper is brass, where it is a mix of copper plus an alloy. Then you have copper plus zinc giving you to bronze, right. Cobalt is heavy. Cobalt is seldom used with all the other combination. For example, they try to use cobalt mixed in iron for precipitation hardness.

They have some applications. Then chromium, which has lot of resistance towards corrosion, is also getting mixed with aluminium, steel, iron, etc. Then magnesium, as such, it is a lightweight material. Earlier nickel was added to steel. Now nickel itself is getting dominating.

So we are trying to keep nickel plus other materials getting added. So it gives you a very high service condition properties, very high strength and very high temperature resistance is given by nickel and its combination. Lead, tin zinc, titanium, tungsten. So all these material are very heavy. Lead, tungsten, they are all heavy metals.

Platinum is expensive. Platinum, gold, silver, all these things play a predominant role in ornamental. So we have placed you type of metals and it is only a small spectrum. This spectrum is chosen depending upon lot of engineering applications.

When we talk about metals, metals are generally classified based on their iron content such as ferrous and non-ferrous material.

Under ferrous also we classify them as steel and Cast Iron . So metals that contain iron are as a primary component, we have steel and alloy of iron and carbon known for its high strength and versatility is steel. Cast iron: iron alloyed with carbon and silicon known for its excellent castability and wear resistance. The difference will be the percentage of carbon. In Cast Iron , the carbon content will be little higher.

Characteristics: typically magnetic, prone to rust and corrosion, without protective treatments and generally possesses very high tensile strength. So, this you should understand. These are the characteristics. So, kitchen pan, a spoon, all are made, fork, then tap, you have adapter, a connector, right. All these things are made out of steel. Cast iron is exhaustively used in church bill.

Ferrous and Non-Ferrous Metals

Non-Ferrous Metals:
Metals that do not contain iron as a primary component. e.g.

- **Aluminum:** Lightweight, corrosion-resistant and highly conductive.
- **Copper:** Excellent electrical and thermal conductivity, corrosion-resistant.
- **Titanium:** High strength-to-weight ratio, corrosion-resistant and used in aerospace and medical applications.

Characteristics: Generally non-magnetic, more resistant to corrosion and often lighter than ferrous metals.

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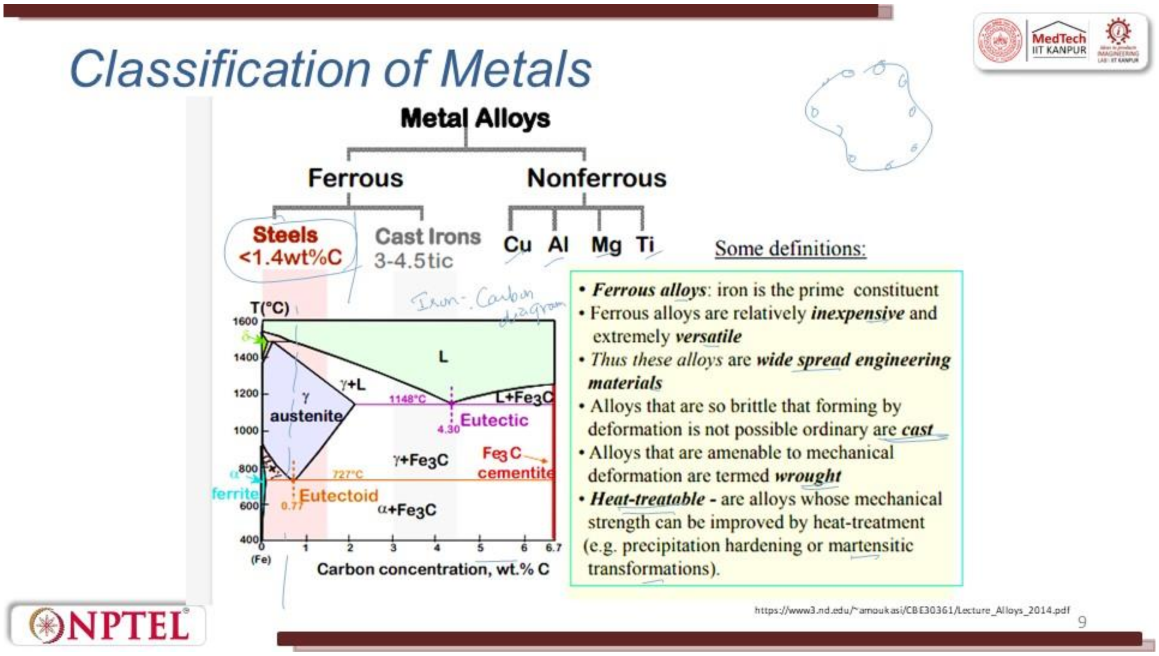
When we talk about non-ferrous, non-ferrous metals that do not contain iron as a primary component are called as non-ferrous material. The most commonly used one are aluminium, copper and titanium. Aluminium is lightweight, corrosion resistance and highly conductive. It is also cost effective.

When we go to copper, it has excellent electrical and thermal conductivity and corrosion resistance. That is why we have geysers. Instant geysers are made out of copper tubes, corrosion resistance. It does not depend upon the water. But after a service condition time, it also needs proper treatment.

Titanium: high strength-to-weight ratio, corrosion-resistance and used in aerospace and medical applications. Characteristics: generally non-magnetic, more resistance to corrosion and often lighter than the ferrous metals. So that is why all these alloys are exhaustively used in automotive bio implants which gets inside body. For low cost, normal household or kitchen utilization appliances, we use these combinations or we use one of these alloys. When we talk about metal alloys, ferrous and non-ferrous, steel falls in a cadre which is less than 1.4 percentage weight of carbon.

Anything more than that will move towards cast iron. Cast iron will have 3 to 4.5 percentage of carbon. When we talk about non-ferrous, the most commonly used is copper, aluminium, magnesium and titanium.



So, this is a typical iron-carbon diagram, which is used for you to understand about the material, what are the different phases of material, which if you want, how do you achieve it? This diagram is called as Iron- Carbon diagram.

Through this diagram, I can try to find out what are the different phases exist. If I want that phase, what should I do? What percentage of carbon should I add such that it tries to produce these phases? Why are these phases very important? These phases in turn dictates the properties or the characteristics of the ion material whatever or ion alloy whatever you use.

So here in the x-axis, you will have carbon content. So the maximum carbon content is 6 to 6.5. Generally, we do not go to that extreme end until and unless it is a specific requirement. So, what does that clearly says? Only this much weight percentage of carbon can be added to iron.

So, in the y-axis, what we have is temperature. Temperature plays a very important role because when the temperature goes high, the solid metal becomes liquid and once it becomes liquid, the addition of carbon becomes easy. How is only carbon getting into it? If you take a simple atom, in an atom, you will have iron atoms are placed in a cuboidal cell and then now the atom radius are of a specific dimension. Now you have carbon which is of a smaller atomic radius which easily finds its space to fit inside the cuboid.

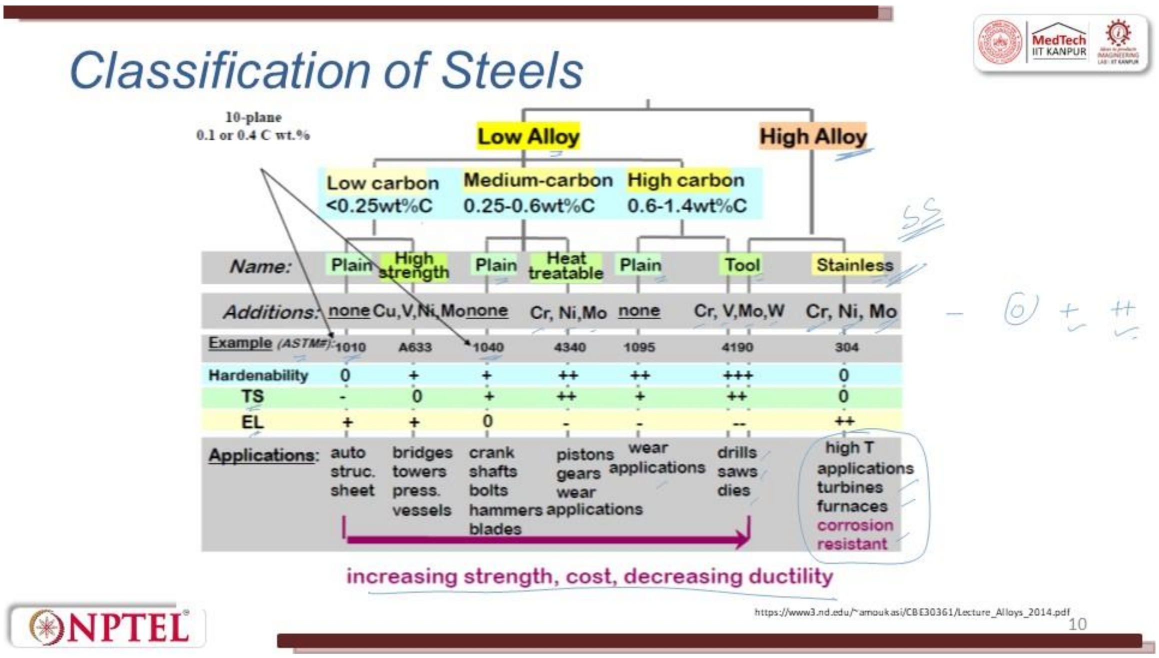
it finds a small its fine space and then it gets inside and then it is present there. So, because of the space and the atomic radius smaller these carbon diffuses inside the iron material. So, how much maximum it can diffuse is 6 to 6.5 weight percentage of carbon. So, in the x axis what you have is temperature. So, if you try to take iron to this particular temperature and bring it back to room temperature, if you start dropping it from here to room temperature, you will try to get all these phases in the final material.

These phases are going to dictate the performance during service condition. As such, this material science itself is a wonderful course. It will have 42 lectures. But for a beginner who is doing introduction to mechanical engineering, I think this information is sufficient enough to keep moving. So, some of the definitions which we are going through.

Ferrous alloys, it is iron is the primary constituent. The ferrous alloys are relatively inexpensive and extremely versatile. Thus, these alloys are widespread engineering material. Alloys that are so brittle that forming by deformation is not possible are generally casted. Alloys that are amenable to mechanical deformation are termed as rot.

The heat which is applied to wherein which you try to add material. So that process is called as heat treatment. Heat treatable are alloys whose mechanical strength can be improved by heat treatment. Precipitation hardening or martensitic transformation. Precipitation hardening is you have carbon, so you have a grain.

So at the grain boundary, these precipitates go and sit. So this is called as Precipitation Hardening. So martensite is like austenite, you will also have martensite. So martensite are generally used, transformation are used to improve the service condition for an application at sub-zero temperature.



So if you look at the classification of a steel, so you can see here it is called as Low Alloy and High Alloy steel.

Under Low Alloy, you can again have low carbon, medium carbon and high carbon. So low carbon is less than 0.25 weight percentage of carbon. Then 0.25 to 0.6 weight percentage of carbon for medium carbon and 0.6 to 1.4 weight percentage of carbon is for high carbon. And what are the other materials? Predominantly it will be iron.

So you can see here under low carbon also, you will have plain carbon and high strength. Then you will have a plain carbon heat treatable, then you will have plain carbon which is used for tools and high alloy are coming in falling under the category of stainless steels. So again here if you see plain, there is no addition of any alloying material or any other elements are not alloyed; high strength you can have copper, vanadium, nickel and molybdenum. So same way here you can whenever I say plain it is there is no addition you apart from carbon. So, heat treatable chromium, nickel, molybdenum is added.

So, when you come to high carbon, it is 0.6 to 1.4 weight percentage of carbon, you will have plain and tool, right. So, under tool you will have chromium, vanadium, molybdenum and tungsten is also used. When you come to stainless steel, chromium, nickel and molybdenum is used, right. So, in according to ASTM standards, we call it as 1010. 1040, 1095, 4190, 304. So in ASTM, we will not call it as give me a low carbon steel. As against that, they always give an ASTM number, aluminium 606, aluminium 1010.

So, they call it like that. So, that is a code which we use and when you go to market, we always say give a material of this ASTM standard code number as 1010, that is how you specify when you buy it in the market. So, when you look at it, here it is very clear; 1010 it is 0.1 here or 0.4 here of carbon weight percentage. So, using this code you go to the market specify and get the material. So, what is all possible, what is not possible we have specified it here.

So, for example, this is hardenability it is medium. So, we have minus 0 plus plus plus, right. So, 0 is in the middle. And when it is plus, it falls, it is okay, doable. Plus, minus, minus, it can be excellently done whatever operation you are trying to do.

For example, hardenability, we have given everything. Then we have tensile strength. This is elongation we have given for all the materials. So where is this plain material used? Automobile, structure, steels.

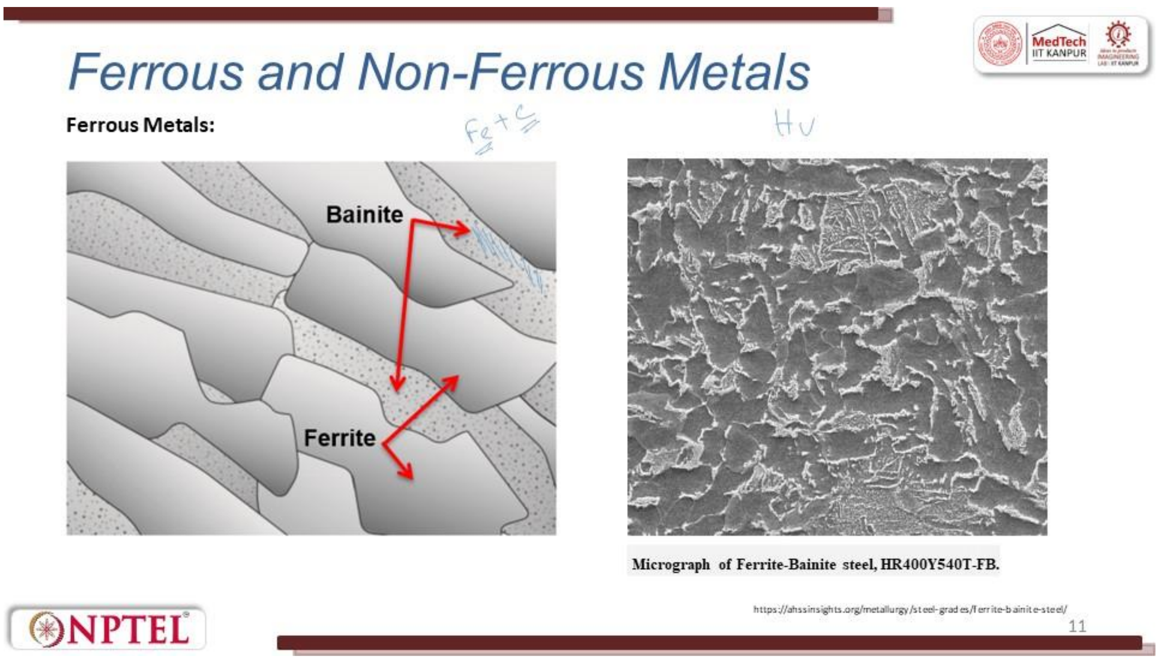
Then high strength material are used in bridges, towers, pressure vessels. Then medium carbon plane we are using in crankshaft, bolt, hammers, blades. Heat treatable we are using it in piston, gear and wear application. High carbon plane we are using in wear application. Tools we are using in drilling tool, turning tool, dies are made out of tools from here.

Stainless steel which is used for turbine blade, furnace application, corrosion resistance application and normal utilities in the kitchen, we use this. So, when we look into it the strength increases, cost increases, ductility decreases. So whenever you are trying to choose a service condition, so we always start like this. We choose the application first. What you are designing for?

And for that part, what are the engineering specifications required? Then we come back and choose what is the alloy. So stainless steel you can see here is a high alloyed stainless steel material. Whatever you buy in the market, we call it as SS stainless steel. SS material has a mixture of chromium, nickel and molybdenum.

Why chromium? It is corrosion resistance. So, you can have multiple alloying elements added and here also you will have many more. For example, silicon will be added, but silicon will be added only for a very small percentage. Some materials are added only to improve the flow ability, only to improve the precipitation, only to improve the ductility.

So, that is there, but here three elements are added. These are dominating as compared to that of the others. The phases, whatever I was trying to talk about here in this graph, if you look at the microstructure, you will see the changes.



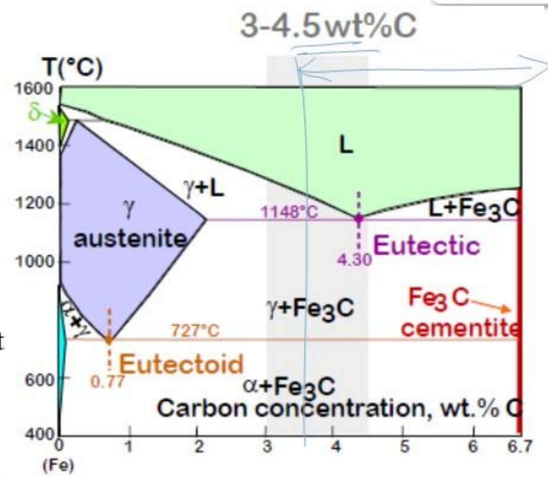
So you can see here, this is ferrite structure, this is bainite structure. So bainite is a combination of iron and iron carbide.

So, because you have taken F and C you have done. So, now in certain places, F will exist as F in certain places, F will be mixed with iron. So, what is the percentage it is getting mixed and these whatever small dots are there, these dots can grow when you play with the temperature, it can grow and it can form small finger impressions like what do you see here. So, and here depending upon the microstructure, the hardness value and ductility response changes. And just by taking to the different temperatures and playing with time, you try to get microstructures of different thing.

Though the starting material is the same, you can get two different microstructures. These two different microstructures signifies that their mechanical properties are different. The extreme end is cast iron.

Cast Iron

- The cast irons are the ferrous alloys with greater that 2.14 wt. % carbon, but typically contain 3-4.5 wt. % of C as well as other alloying elements, such as **silicon** (~3 wt..%) which controls kinetics of carbide formation.
- These alloys have relatively low melting points (1150-1300°C), do not formed undesirable surface films when poured, and undergo moderate shrinkage during solidification. Thus can be easily melted and amenable to ***casting***



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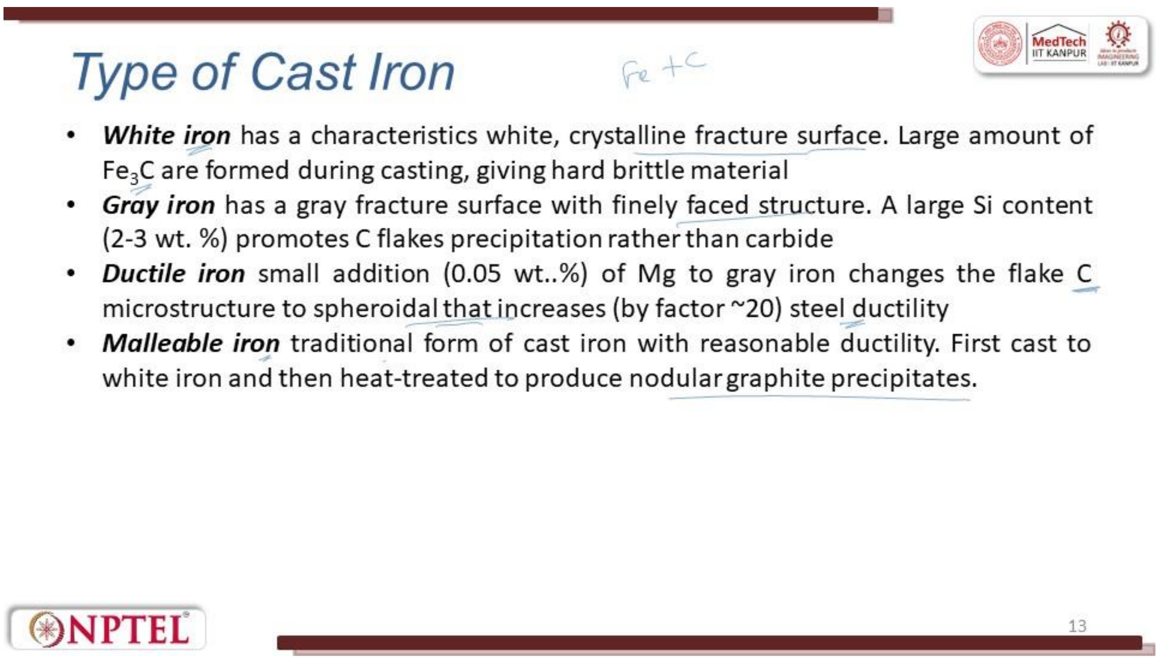
Cast iron are the ferrous alloys with greater than 2.14 weight percentage of carbon. They typically contain 3 to 4.5 percentage weight of C as well as other alloying elements like silicon which controls kinetics of carbide formation.

So we are talking about here. Somewhere from here, we are talking. These alloys have relatively low melting point between 1150 to 1300, do not form undesirable surface films when poured and undergoes moderate shrinkage during solidification. Thus, can be easily melted and amenable for casting. So, we have not discussed more about thermal conductivity.

Thermal conductivity is one thing wherein which the conduction happens through the material. The other thing is specific heat and that combination leads to a shrinkage of the material. For example, when you start pouring a hot liquid and then allowing it to cure to room temperature, it always shrinks. Some material shrinks larger, some does it smaller. So, shrinkage also plays an important role.

So, when we have cast iron material, we always go for heat treatment and we take it to a liquid state. From a liquid state, we try to pour it inside a confined space that is called as a die to get the required part whatever you need. So, when you do that, when you go to very high temperatures and when you are coming back to room temperature, it is prone for oxidation. For example, in aluminium, it always forms a thin film on top of a aluminium. Just a fresh aluminium, when you scratch it, it immediately oxidizes.

But here in cast iron, it does not oxidize and you can try to take it to high temperature and pour it inside a confined space. It does shrinking, but it is not so much oxidized. So it tries to replicate whatever shape we have in the die.



Again in Cast Iron, we have classifications. One is white iron, grey iron, ductile iron and malleable iron.

Like what we saw in steel. You should also understand in cast iron where there is a high carbon content, they are also classified. What is white iron? As a characteristic white, crystalline fractured surface, large amount of Fe3C, as I told you, Fe plus C, combination, whatever it is mixing, Fe3C. Fe3C is a carbide, are formed during casting, giving hard brittle material.

Suppose you are looking for some applications wherein which it has to take lot of impact load. Toughness should be very high. Hardness should be high or low. So grey cast iron has a grey fractured surface. When you try to fracture it, it looks white.

When you try to fracture it, it looks grey. Fracture is break, right, with fine-faced structures. Your crystalline fractured structure, fine-faced structure. A large silicon content, 2 to 3 percentage weight, promotes sea flakes precipitation rather than carbide. Ductile iron, small amount, 0.05 weight percentage of magnesium to gray cast iron changes the flakes sea microstructure to spheroidal that increases the ductility.

So, now you are trying to play with the structure. So, this improves the ductility. The last one is malleable iron. Traditional form of cast iron with reasonable ductility. First cast to a white iron and then heat treat to produce nodular graphite precipitates.

See, if you look into ancient technology civilization or ancient culture like go to temples or go to kingdoms or go to museums where they will display the king's door or his sword, whatever it is. They will always have lot of cast iron because that gives them the freedom of shape. They used to cast it and then they used to attach it with a sword. The beautiful architecture which is made in a temple door, majority of them will be casted. And in order to take a shape, they will also try to use metal forming techniques, but majority of them where you have fine features to be made, they will always be doing it by casting.

Thank you very much.