Nature and Properties of Materials
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Lecture 11
Metals 1

Good morning students, so fortified by the knowledge of crystal structure now we will start our journey with some materials, which shows regular crystal structure. So we have 1st chosen the metals in this journey and among the metals there are many metals, we are going to first talk about Iron and Iron alloys.

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So hence in this particular lecture, I am going to talk about classification of ferrous alloys, various types of steels, the effect of impurities and also another Iron based alloy which is the composite you can say, it is not exactly alloy, which is the cast Iron, so these are the things that we are planning to discuss today. Now, when we are talking about metallic alloys okay, so there are 2 basic classifications of metallic alloys.

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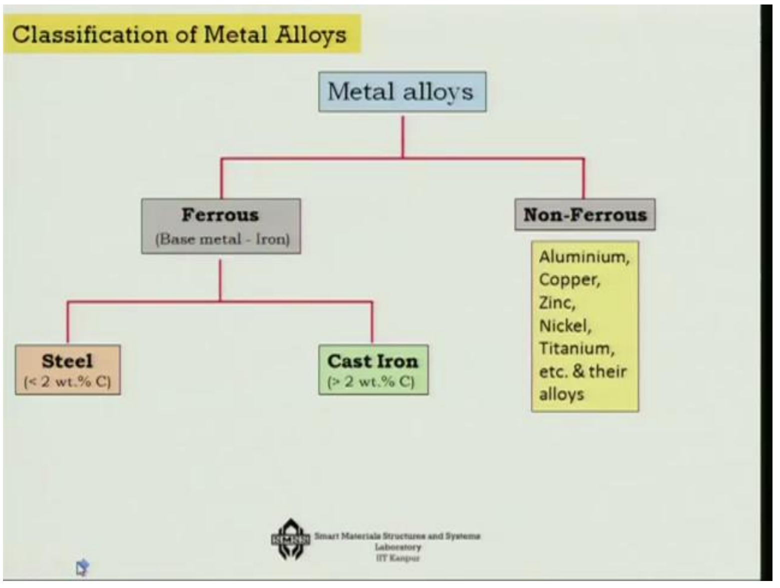

One is the ferrous group where the base metal is Iron and another is the non-ferrous group, where base metal can be anything like Aluminum, Copper, and Zinc at times not very much, but Nickel, Titanium okay and their alloys itself. Now, Iron based alloys are classically speaking that they are much more extensive in terms of use and also they are in use for a very long time.

If you remember, I have shown you the evolution of Materials where Iron came 1st and it is steel having a very large base mostly as one of the minerals Iron is quite abundant on earth. But interesting thing is that in fact aluminum is more abundant than Iron. The problem is that extracting Aluminum is something which is like a high energy procedure.

So it is so energy intensive in order to get Aluminum from the earth crust that that is why it is relatively less popular than Iron and less relatively more expensive than Iron even though Aluminum is much more abundant in the earth crust. Now, in terms of Iron based different types of alloys or say composites, broad 2 things that we can say is that steel as one of the alloys and cast Iron.

I would not exactly say cast Iron as an alloy, but rather I will call it to be a composite okay. The logic behind that I will explain when I will talk about the composites. Basically, when we discuss about a composite, we say that the constituents remain in a distinct a separation state okay. They do not chemically get interlinked with each other, so that is what happens when the percentage of Carbon is so high in a system like in Iron that Carbon starts to precipitate and actually form a form of a composite.

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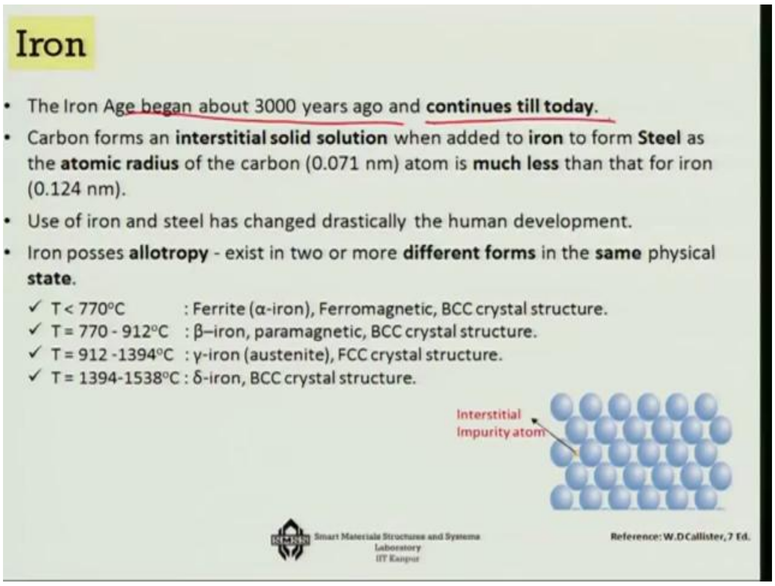

On the other hand, steel is a kind of a mixing where Carbon atoms penetrate inside the Iron crystal structure and thus not only Carbon, but similar impurities thus actually forms the alloys. So the journey with the Iron as I earlier told you that it began around about 3000 years and it is still continued today okay. And one the most important alloy material in Iron is actually Carbon, which forms an interstitial solid solution. Now what is this interstitial solid solution?

First of all, solid solutions means that the both the solvent and the solvent both of them are the solid state itself in this case the Iron and the Carbon, then how do you get the solution? The Carbon atoms which are actually of atomic radius something like 0.071 nanometre is actually much smaller than the Iron atom which is like 0.124 nanometre.

Now, if you consider an Iron crystal structure, are these atoms are bigger in size if you look at it, consider these 3 atoms, then the space that is created in between okay. That space is easily suitable for one Carbon and that is the interstitial space, okay. So there are actually 2 different types of solute solution possible; one is interstitial solid solution and another is substitutional solid solution.

Now, substitutional solid solution actually happens when the impurity, the atomic radius of the impurity is of the same order as the base material. On the other hand, in this case since the atoms are very small, so they actually do not substitute any atom but they basically go to the space between the atoms. So thus the steel is formed when Carbon goes into the space between the Iron atoms. What is the significance of this?

Actually, this has changed dramatically the human development why, because the moment the Carbon goes inside, then if because of the presence of this, these atomic bonds are under stress and dislocation be it Edge dislocation, be it Edge dislocation or be it some other type of Screw dislocation, they get actually stopped by this interstitial atom.

And a result the dislocation gets stopped, so we will see later on that it affects the hardness, strength in a very favorable manner. Now regarding Iron, one more important thing we have to keep in mind that just like Carbon, Iron possessed many allotropies and this allotropy different forms in the same physical state are actually function of temperature.

For example, less than 770 degree, you will always see the Alpha Iron or ferrite okay, these are actually BCC crystal structure these are ferromagnetic in nature. As you increase the temperature from 770 to 912 approximately, you get the Beta Iron, which is not ferromagnetic, it is paramagnetic and but it has the BCC Crystal structure.

If you go from 912 to about 1394, you will get another version which is known as the Gamma Iron and this is not BCC any more, this has a FCC crystal structure, which is also called Austenite crystal structure. Again, beyond 1394 to 1538, you get another Iron crystal structure in another phase of Iron which is Delta Iron and it has a BCC crystal structure.

So where are we, we start from BCC, again at highest temperature we have BCC, but ferromagnetic to paramagnetic, then from BCC we go to FCC and at a even higher temperature we go to BCC. That is how the Alpha, Beta, Gamma, and Delta that is how the Iron phases and the allotropies of Iron are actually distributed.

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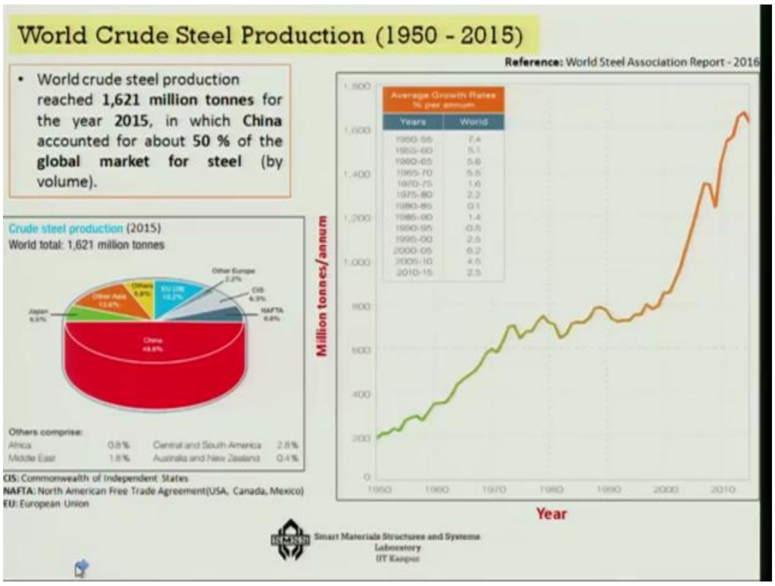

Now, the penetration of Carbon as I told you into Iron had a very significant actually economic effect. If you look at it that what is the crude production in the kind of 65 years between 1950 to 2015 okay, so the World Steel Association of 2016, you would see that about 1621 million tons for 2015, about 50% is from China okay and then rest is from rest of the world, so that is what you can see it in the picture.

China is there, Japan is there okay and other Asian countries are there. Of course, India has many very good steelmakers today in Indian context. So as you can see that even though there are some ups and downs, but by and large this curve is always increasing in terms of million tons of steel per annum.

In fact, we always say that the growth of an economy is steel is very much kind of depicted by the production of Iron and steel, so that is something that you can see that that is how it is happening.

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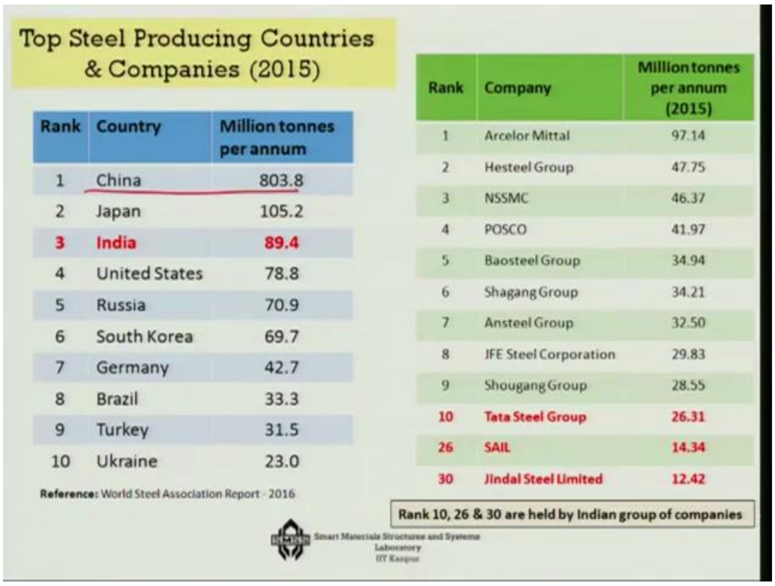

But if you look at the picture country wise, you would see that some of the highest developing countries like China has 803.8 million tons per annum steel production capability, Japan 105.2 and India is number 3 89.4, United States is lower than that 78.8, then Russia, South Korea, Germany, Brazil, Turkey, etcetera.

In terms of companies also, there is one company which is in the top of the list Arcelor and Mittal together, then there is Indian contribution is there that is 97.14 million tons. And also if you look at number 10, Tata steel group 26.31 million tons or SAIL or Jindal, we really have world presence in terms of million terms of steel per annum production. That is why steel is one of the very important materials for our economy.

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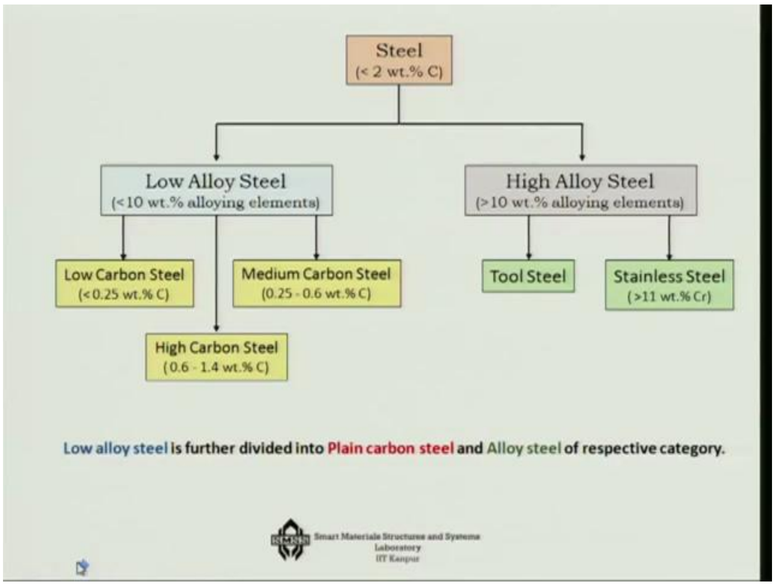

Now, steel we know that it is a solid solution which has the interstitial Carbon present in it. But the presence of Carbon is smaller, it is less than 2 wt %, if it becomes more than we go to the cast Iron okay. So if it is less than we get steel, but even that itself has many variations.

For example, depending on the presence of other alloying elements, if there is less than 10 wt % of other alloying elements, then this Carbon and other element composition will make the low alloy steel. If it is greater than 10 wt %, then we are going to get the high alloy steel. Now, among the low alloy steel itself there are 3 different types, one is the low Carbon steel, which has less than 0.258% of Carbon and then medium 0.25 to 0.6 and high Carbon steel, 0.6 to 1.4%.

Among the high alloy steel again that means which has greater than 10 wt % of alloying elements, again there are 2 subgroups one is for the Tool steel and another is for the Stainless steel. Now, Stainless steel is very much distinctly classified because of the presence of chromium in it okay. Greater than 11% presence of chromium gives steel the quality that it will not get corroded very easily at all and that is how the stainless steel that name comes into picture okay.

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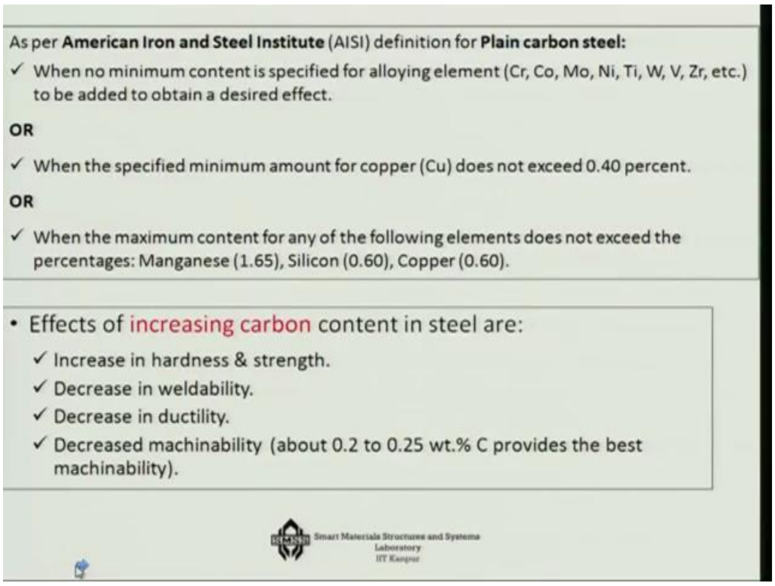

Now, when you are talking about plain Carbon steel because this low alloy steels out of that there is this plain Carbon steel and what we mean by it, so there is a AISI definition of it that says that if you do not specify the presence of the minimum content of materials like Carbon, Cobalt, Molybdenum, okay Nickel, Titanium, Tungsten, Vanadium, Zirconium, etcetera, if you do not specify the minimum content to be added to obtain a desired effect, then that would be one qualifying point for plain Carbon steel.

Again, the Copper also should not be more than 0.4%. And finally the maximum contains recipe for Manganese to 1.65, Silicon to 0.6 and Copper to 0.6. So that means copper must be in the range of 0.4 to 0.6, manganese should not be more than 1.65% wt % and silicon should not be more than 0.6 wt % and rest of the materials should be present but the minimum content is not specified, in such cases we will actually consider this to be plain Carbon steel.

And what happens in terms of the Carbon content is that as I increase the Carbon content, my hardness and strength increases, but that comes with a cost because if the hardness and strength increases, there will be definitely a decrease in ductility, there will be decrease in weld ability, there will be decrease in machine ability of the system. So for example, about 0.2 to 0.25%, Carbon provides the best machinability.

So hence, while increasing Carbon you are gaining in terms of hardness and strength, but you are actually losing in terms of ductility, malleability, machinability, weldability, etcetera, so there is a trade off there that is what guides us towards exactly how much is good enough for a particular product. Now, the most versatile among the steel is the low Carbon steel, which contains about 0.25 wt % of Carbon.

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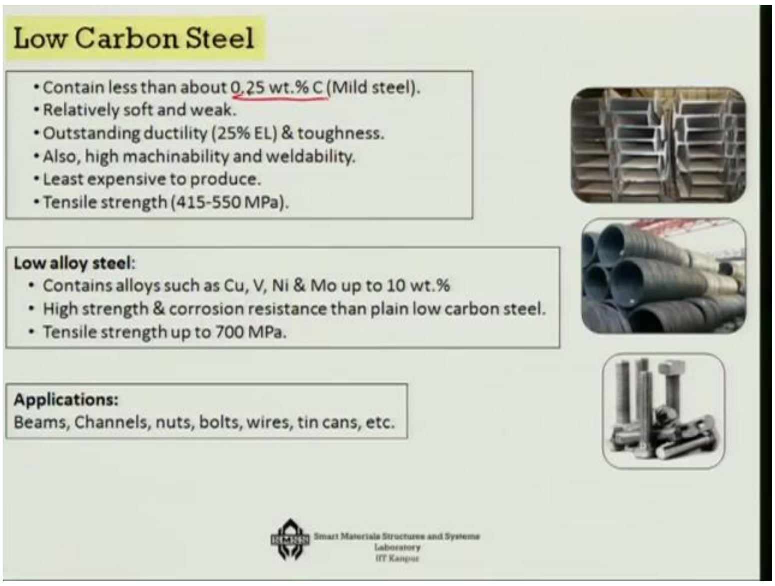

So because the Carbon% is low, it is relatively soft and also it is weak. It has ductility like 25% and toughness, and also it has machinability, weldability and it is less expensive to produce and its tensile strength is of the order of 415 to 515MPa. Now, low Carbon steel is used for general steel applications where the strength is not on high demand, this is generally known as the Mild steel.

There is version which is called the low alloy steel, which gives you a better strength that is 700MPa and in this you actually get more alloying element for example, you get Copper, Vanadium, Nickel and Molybdenum upto10 wt %, more than that it will become high alloy. So that is a low alloy steel that has better tensile strength and has many structural applications like beams for example or channels or nuts and bolts for example, wires, tin cans, etc, so that is about the low Carbon steel.

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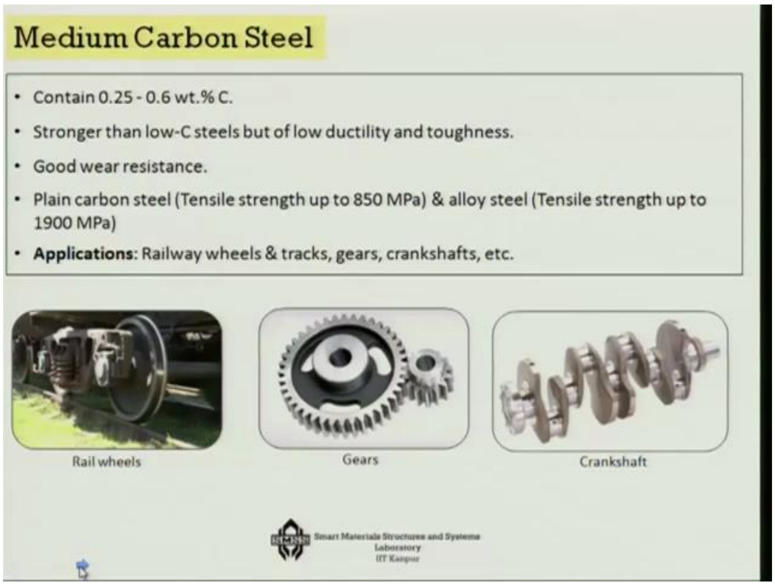

Now if my Carbon content gets increased a little more, 0.25 to 0.6 wt %, what we get is a medium Carbon steel. These are stronger than low Carbon steels, so your strength increased, but of low ductility and toughness, you have sacrificed in terms of that. But it has good wear resistance, strength has increased, tensile strength is up to 850MPa for plain Carbon and if you alloy it further, you can go up to 1900MPa of tensile strength.

No wonder that that is why it has heavy duty applications like railway wheels or tracks itself or gears or crankshafts, okay, so wherever you need a high tensile strength okay and toughness so that is something that you get actually in the medium Carbon steel.

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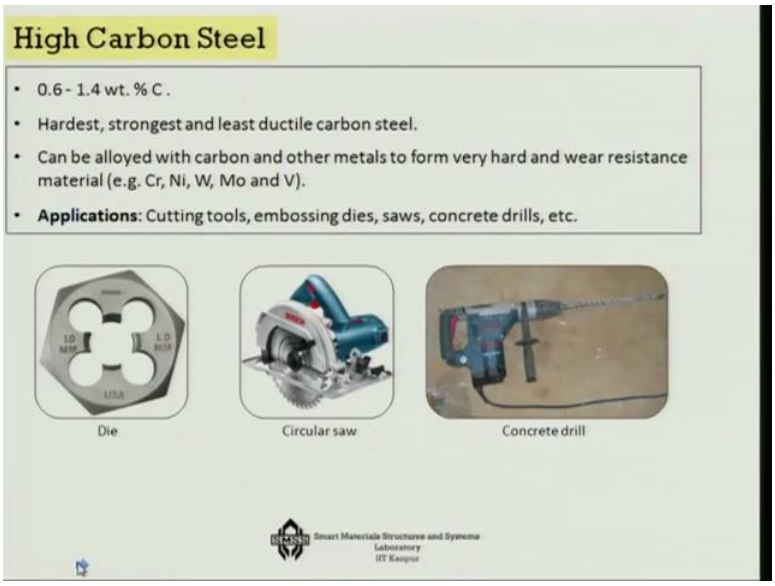

Now finally, I find this the Carbon more then I go from 0.6 to 1.4 wt % of Carbon, this one is the hardest, strongest, but least ductile Carbon steel okay. That is why it is used generally for die for example or this type of applications. It can be further alloy with Carbon and other metals to form very hard and wear resistant material like if you Alloy it with Chromium, Nickel okay, tungsten, Molybdenum or Vanadium, you get actually something which has better wear resistance for example.

And then you can use it for cutting tools, for embossing dies, for saws, concrete drills, these types of high strength applications you can actually use this system. Now what happens, so far we have kept our alloy percentage less than 10 wt %, we only varied the Carbon % from low Carbon to medium Carbon to high Carbon.

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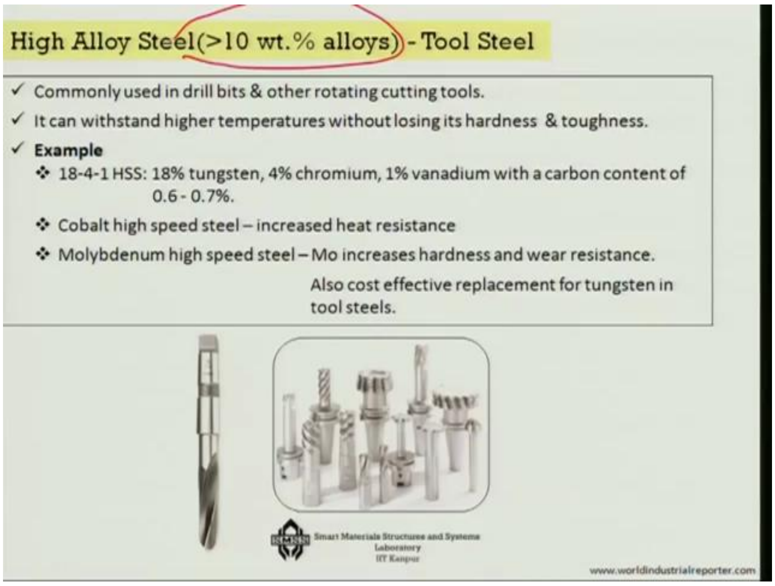

If alloy percentage itself increases goes to greater than 10% okay for example, for drill bits and other rotating cutting tools, what happens is that you can withstand higher temperature without losing the hardness and toughness. For example, the high speed steel like 18-4-1 that means it has 18% tungsten and 4% chromium and 1% vanadium and Carbon content which is about 0.6 to 0.7, so how much wt % we are getting, 23.7%, greater than 10 wt % of alloys

You get a very good quality high alloy steel okay, which can be used in terms of actually tools. Cobalt high-speed steel another example, you can use it for increased resistance or Molybdenum HSS, where molybdenum will increase the hardness and wear resistance and also it will become cost effective because we are replacing tungsten in the tool steel. So all these high alloy steels are mostly used as cutting tools and drill bits.

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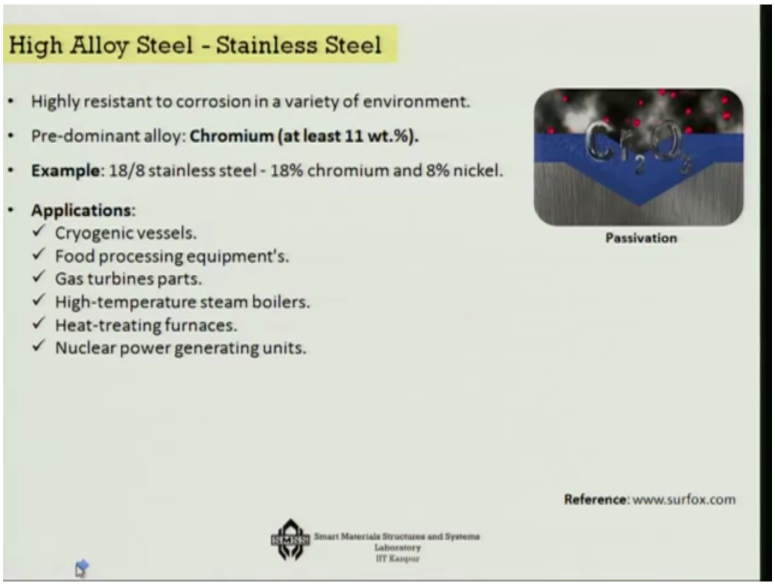

Now, there is another group of high alloy steel which also has greater than 10 wt % of alloying material, but it has a single most very important alloying material that why it is a separate class that is chromium, at least 11 wt %. The presence of chromium gives it high resistance to corrosion for example, the 18/8 stainless steel has 18% chromium and 8% Nickel; this gives it a very high resistance to corrosion.

That is why they are applied for applications like cryogenic vessels, food processing, gas turbine, high temperature steam boilers, heat treating furnace, nuclear power generating units, various other types of boilers okay, so they are used, so that is about the stainless steel. Now, let us look into all the alloying elements and their effects in terms of a chart, not all but most of the significant ones.

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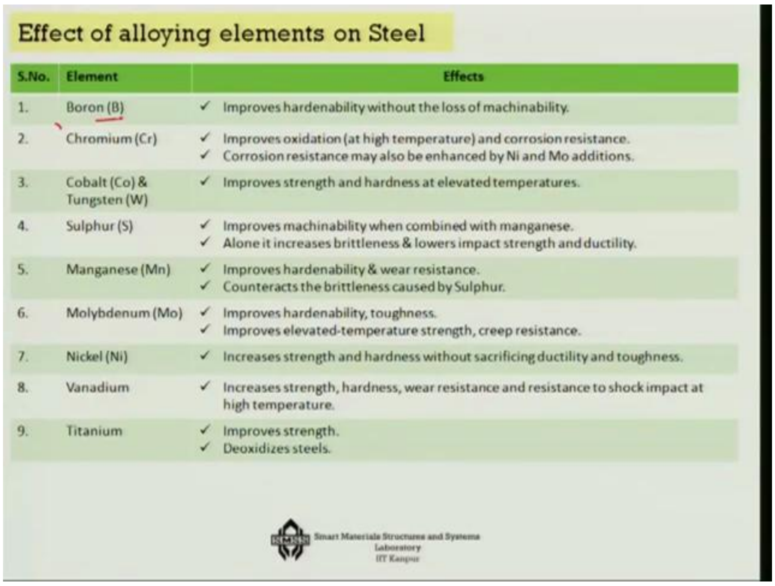

Effect of alloying elements on Steel

S.No.	Element	Effects
1.	Boron (B)	✓ Improves hardenability without the loss of machinability.
2.	Chromium (Cr)	✓ Improves oxidation (at high temperature) and corrosion resistance. ✓ Corrosion resistance may also be enhanced by Ni and Mo additions.
3.	Cobalt (Co) & Tungsten (W)	✓ Improves strength and hardness at elevated temperatures.
4.	Sulphur (S)	✓ Improves machinability when combined with manganese. ✓ Alone it increases brittleness & lowers impact strength and ductility.
5.	Manganese (Mn)	✓ Improves hardenability & wear resistance. ✓ Counteracts the brittleness caused by Sulphur.
6.	Molybdenum (Mo)	✓ Improves hardenability, toughness. ✓ Improves elevated-temperature strength, creep resistance.
7.	Nickel (Ni)	✓ Increases strength and hardness without sacrificing ductility and toughness.
8.	Vanadium	✓ Increases strength, hardness, wear resistance and resistance to shock impact at high temperature.
9.	Titanium	✓ Improves strength. ✓ Deoxidizes steels.

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Like the Boron, it improves the hardenability without the loss of machinability. Chromium, it improves the oxidation and corrosion resistance, so basically that is why stainless is much more corrosion resistant. Corrosion resistance may also be enhanced by Nickel and Molybdenum ratio. Boron very interestingly, even though it is inorganic material, it actually is used for making even composites which I will talk about later on, which is used for making materials like Space shuttle because it has very good high temperature property.

Cobalt and tungsten, they are generally used to improve strength and hardness at high temperature. Sulphur improves the machinability, when particularly combined with manganese, but it increases the brittleness and lowers impact strength. In that condition I will also like to tell you that Sulphur was one of the most important component in the earlier minerals the Iron ores that are found in India.

And that of course gave it as an excellent corrosion resistance both Sulphur and Phosphorus. Manganese improves the hardenability and wear resistance and it counteracts the brittleness caused by Sulphur. Molybdenum improves again hardenability and toughness and it improves particularly the elevated temperatures, strength, creep resistance, etcetera. Nickel increases strength and hardness without sacrificing the ductility and toughness.

Vanadium increases strength, hardness, wears resistance and resistance to shock impact at high temperature and Titanium improves both strength and as well as deoxidizes the steel. So these are like some of the contributions of the alloying elements into the property of the steel, which if we know we should be able to give proper guidance in terms of steel alloy making.

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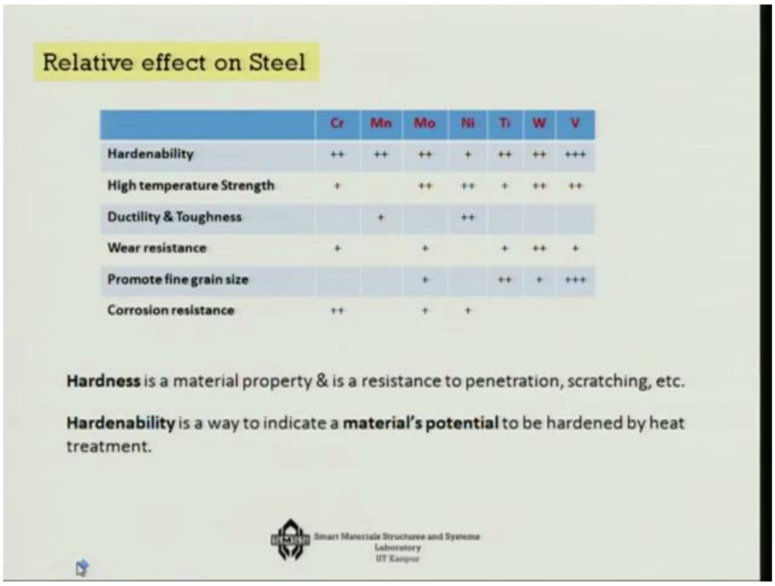

Now suppose you have some property in mind, you can use this table. Like the hardenability, what is hardenability? It is a way to indicate a material's potential to be hardened by heat treatment. Now if I want to increase this hardenability through heat treatment, we should go for Chromium, Manganese, Molybdenum and Titanium and Then Tungsten and Vanadium. Particularly, Vanadium is very good in terms increasing the material's potential to be hardened.

If you talk about the high temperature strength, then Molybdenum Alloy, Nickel, Tungsten, Molybdenum, these are actually very good. Ductility and toughness point of view, on the other hand Nickel is good. Wear resistance point of view this particular Tungsten alloy is good. And to promote the fine grain size Vanadium is good, for corrosion resistance point of view, Chromium is good.

So thus, each one of these alloying materials has its unique contribution into the property of the steel alloys. Finally, we are going to talk about the cast Iron okay and where you have the percentage of Carbon which is even more than what you have seen earlier in mild steel, etcetera that is greater than 2 wt % Carbon that is the cast Iron okay system that we are talking about.

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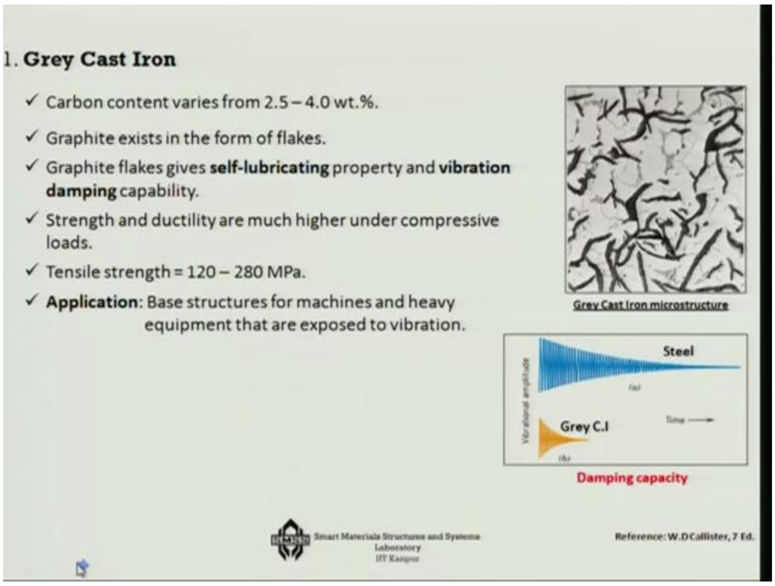

Now, there are quite a few variations of cast Iron, one first that we should see from vibration application point of view, I liked it is the Grey cast Iron okay. It has Carbon content which varies from 2.5% to 4%. And here the graphite remember, this is a high Carbon content we are talking about, the graphite here exists actually in the form of flakes as you can see each one of these flakes.

And this graphite flakes give it an excellent self lubricating and vibration damping capability. The strength and ductility are much higher under competitive loads and the tensile strength is somewhere between 120 to 280MPa. This is being applied in structures like for machines, the foundation structure or heavy equipments that are exposed to vibration. In all these cases, the Grey cast Iron is definitely one of the most popular one.

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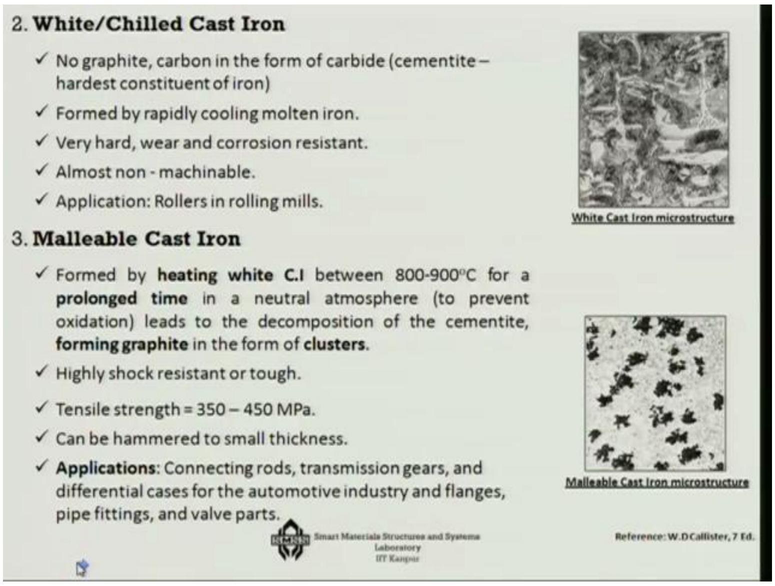

Then the other variation that we have is called the White or Chilled cast Iron. In this, no graphite formation or takes place Carbon element in the form of carbide. It is generally formed by rapid cooling of molten Iron, it is very hard, wear and corrosion resistance, it is almost non machineable and application is something likes rollers in the rolling mills.

Then there is the Malleable Cast Iron, which is formed by heating white or chilled cast Iron between 800 to 900 degree centigrade for a prolonged time in a neutral atmosphere to prevent oxidation and which would lead to a decomposition of the cementite forming graphite in the form of clusters. Now, these are highly shock resistant, tensile strength is between 350 to 450MPa, it can be hammered also to small thickness.

And it is used typically like for the connecting rods or transmission gears and differential cases for the automotive industry and flangers, pipe fittings and the valve parts. Now let us look at some other form of cast Iron like the Ductile or the Nodular so to say this Spheriodal cast Iron.

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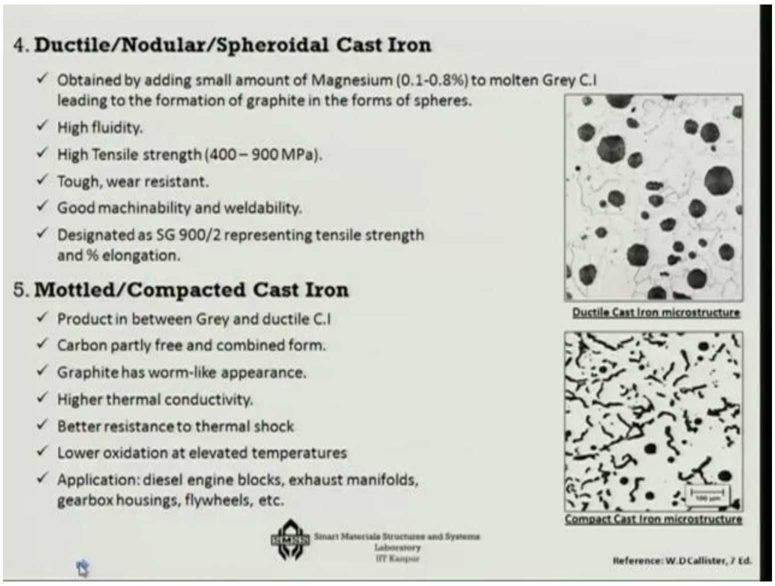

Now incidentally, when you actually extract Iron from the sea unlike the plain, we actually extracted mostly in the form of Nodular Iron. So similarly, you can think of designing your own Nodular Iron, which you can do by adding small amount of magnesium 0.1 to 0.8% to molten Grey cast Iron leading to the formation of graphite in the forms of spheres. It has high fluidity and high tensile strength, it is tough and wear resistant, good machinability and weldability and it is designed as SG 900/2 representing tensile strength and percentage elongation.

The next one is actually Mottled or Compacted cast Iron. This is usually initially made using Grey and ductile cast Iron. The Carbon remains in both the stages partly free and combined form, graphite has a worm like appearance and the system has higher thermal conductivity, it has better resistance to thermal shock, lower oxidation at elevated temperatures. When you say applications are in the field of diesel engine blocks or exhaust manifolds, gearbox housings, flywheels, etcetera.

So if you look at the structure of both of them for example, for the ductile Iron, you can see that this by just by adding a small amount of Magnesium, you can of course control indirectly the formation of Graphite, you can see it here. And that actually gives this as a good machinability and weldability because as I told you that graphite increases, it works like lubrication. In terms of the Compacted cast Iron, you can see that it is in between grey and the ductile cast Iron because the graphite formation is here, but not actually to a very high degree.

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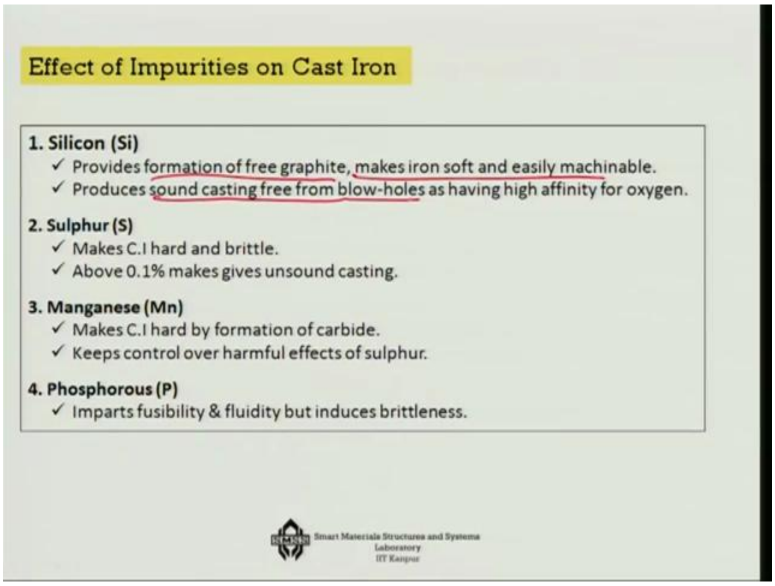

So that is about some of the cast Irons, now the effects of impurities on cast Irons are, suppose if I add silicon as an impurity, then it provides the formation of the graphite favors it actually, makes Iron soft and easily machineable and provides sound casting free from blowholes as having high affinity to oxygen.

If I add Sulphur, the cast Iron will become hard and brittle and about 0.1% it gives very unsound casting, so you should not give at all too much of Sulphur. If I add Manganese, it will make it hard by formation of different types of alloys, but it keeps control over harmful effects of Sulphur. If I take Phosphorus, it imparts fusibility and fluidity, but it also induces brittleness, so we have to add it in a very limited manner.

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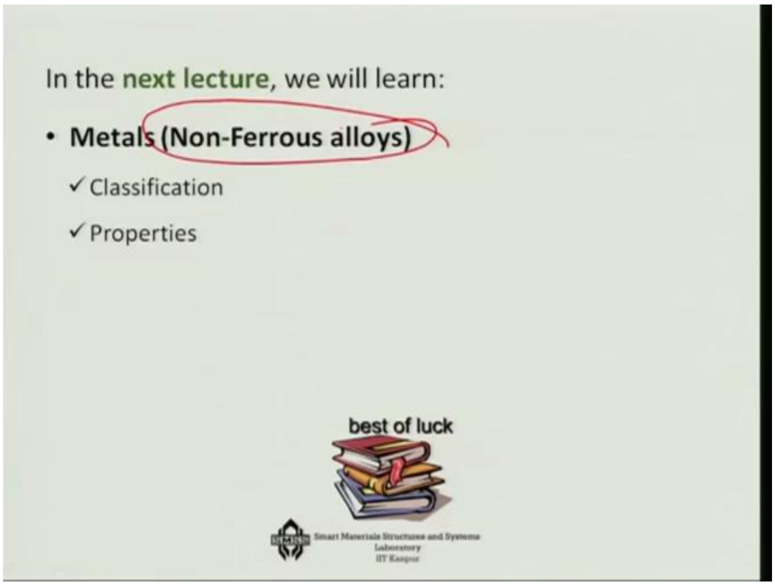

Now this is where we will complete our journey of the Iron based alloys. In the next lecture, we will talk about nonferrous alloys, their classification and their properties, thank you.