Carbon Materials and Manufacturing
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Lecture - 04
Story of Carbon: Carbon in Technology

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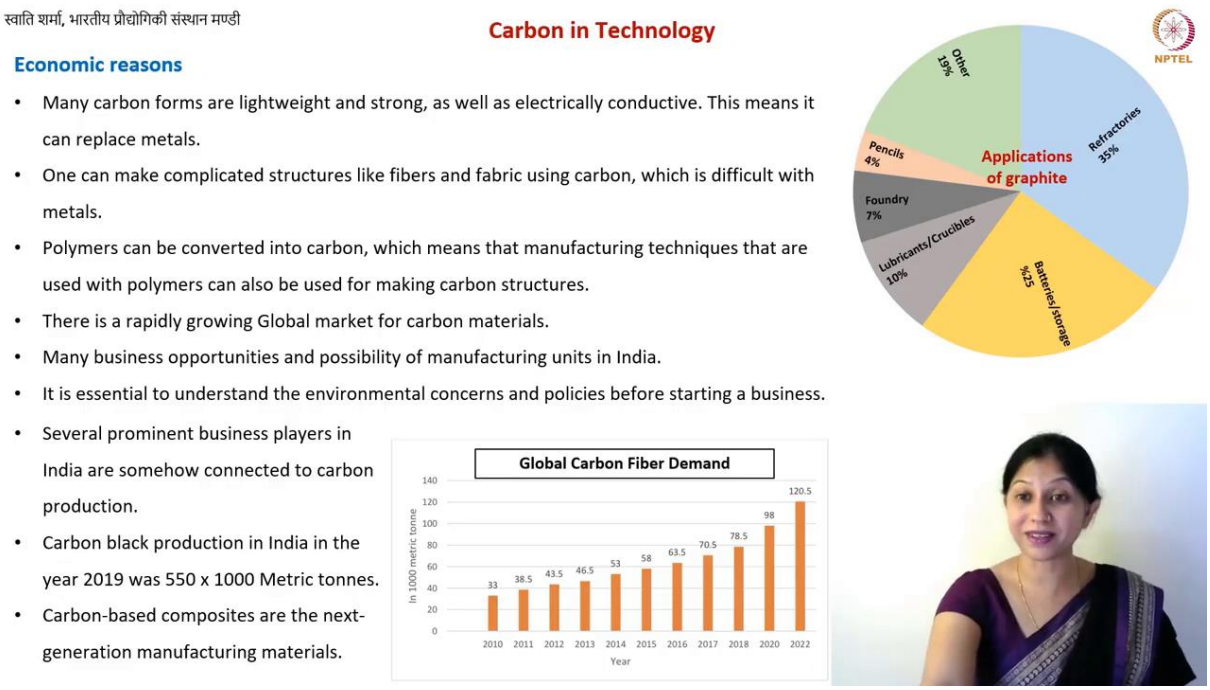

Hello everyone. So, in the previous lecture, we learned that carbon is a very important material because it is present everywhere, we are a carbon-based life form. It is also an element that is present in outer space and carbonaceous materials tell us a lot about the possibility of life. And we can understand the evolution of life on our planet by understanding carbon materials.

Now, you might tell me that I do not care about all these things, I am taking this course because I want to get a good job in a company. In that case, let me tell you carbon is also a very important technological material. What is a technological material? Material that is used for a lot of manufacturing purposes for making things. Now, these are the economic reasons for learning carbon.

So, I told you in the previous lecture that carbon is a lights element. So, most of the carbon materials happen to be very lightweight and they are very mechanically very strong. Because carbon forms these long sheets like molecules and these are covalent bonds which are actually

very strong bonds. And that is why you have light and strong. And this is a very important property of a lot of carbon materials.

Why do you require light and strong materials? Nowadays for example, if you think about an aircraft for aircraft applications for making the body of the aircraft, various parts also the blades of your gas turbine, the turbo engine.

So, what do you require? You need materials that can withstand high temperatures, that is mechanically very strong and preferably lightweight. So, nowadays for many applications, we are still dependent on metals and alloys in superalloys.

But these things can be replaced potentially or some of them have already been replaced by these nice carbon materials which have the desired mechanical strength and lightweight property of carbon. Now, one more important thing is that for many applications you require materials that have electrical conductivity and that is the reason we use metals. Graphite or graphite-like carbons do have an electrical conductivity that is not as high as that of metals. In fact, graphite is a semimetal, not a semiconductor or not a conductor in the traditional way. So, you call it a semi-metal, maybe in one of the lectures I will explain to you based on the band structure, why do we call it semi-metal?

The point is that graphite has a reasonably high electrical conductivity, although lower than that of metals and sometimes you can have some additives also in graphite and all graphite-like carbons, then you can get high conductivity structures. So, now, you got everything you need like the weight is good, you know its mechanical strength is good. Graphite or graphitic carbons are thermally conductive in most cases.

So, we are not talking about diamond here, but on the other hand, diamond is a much lower fraction of carbon on earth or diamond-like carbon. So, most of the carbons are graphite-like structures because graphite is the most stable thermodynamically favourable form of carbon. So, now, all of these carbon materials have very nice properties. So, that is why they are already replacing metals in many industrial applications.

Here I have drawn this chart (refer to slides), which is based on a very you know quick internet search. So, the numbers might not be perfect, but just to give you an idea that these are some of the common applications of graphite. You all have seen graphite in your pencil, but you probably did not realize that a lot of batteries that you are using also contain graphite electrodes.

Other than that, graphite is used as a solid lubricant, you also probably know that graphite can withstand the very high temperature of its thermal properties, hence it is used in the foundries. It is a very important refractory material as well, for example in the casting you are using sand as a refractory material.

Similarly, graphite is used for more specialized and more sophisticated casts. So, these were some of the applications of graphite. Similarly, graphite-like carbons or graphitic carbons; again, we will learn about the definition of what is called graphitic and what is not. But these type of carbon materials are of high industrial relevance. So, these are very important technological materials.

Now, you can make fibers from carbon, you must have heard carbon fiber. nowadays carbon fiber is very important for any manufacturing engineer. A lot of things, you see now like the cars that are made of carbon fibers, the bodies of aircrafts are being made of carbon fibers. And, this has already reached the production stage, the industrial manufacturing states. It is not a research topic anymore.

People are using carbon fibers and composite materials based on carbon fibers for a lot of applications. So, carbon also gives you this flexibility of making structures like fibers. You will say how do I make carb fibers from carbon? Because if you take your graphite from the pencil; it does not look elastic. So, how do you pull fibers from it? The idea is actually to make polymer structures. So, you make these fibers into a polymer and then you convert them into carbon.

This is one of the most important processes for this entire course, for example, certain petrochemicals, cokes and pitches which are high in carbon content, how do you convert them into carbon? This is a process that has been industrially used for manufacturing graphite, for manufacturing glass-like carbon for a lot of other activated carbon.

So, for all these large-scale carbon materials, this technique has been used for several decades. What you can also do is, you can make fibers out of petroleum pitch and convert those fibers into carbon. Here I have also shown a graph where you see the global demand for carbon fiber. So, you can see that there is an increase. So, this is up to 2020.

Again this is based on a quick internet search, numbers may not be perfect; I have not shown any error bars or anything. The point is that I just wanted to show you the trend, the increasing

trend, 2022 is the last one that is the predicted one and it might actually exponentially grow. So, all over the world, there is a rapidly increasing demand for carbon fiber manufacturing.

Now, it is not just carbon fiber, there are other carbon materials as well. So, I have just shown carbon fiber, but also for carbon black or for many other carbon materials there is increasing demand. Now, because of this demand, of course, you also need supply. So, you have several business opportunities, not just in India but all over the world.

But I am talking about India because nowadays we are promoting manufacturing in India. So, there are a lot of business opportunities. Not just the bigger companies, but also there are many small manufacturers of different carbon materials in India as well as all over the world. Now, one thing I must tell you if you want to have a startup or you want to make carbon fibers, that is wonderful., we should do manufacturing, but whenever you are working with carbon or carbon-based manufacturing, you must take care of the environmental pollution aspects. The reason is that whenever you are heating a polymer, you will be getting rid of the non-carbon atoms.

And where do these atoms go? They either form tars or they form some sort of black carbon, brown carbon and so on. These things can prevent them from going back into the environment. There is a possibility of catching these things, for example, using specialized filters, you can even pass these gases through water and then catch a lot of them already. So, the point is not that you should not do manufacturing, I mean by this logic we should never do any manufacturing in the world, then there will be no pollution. Then we also should stop driving cars, then there will be no pollution.

We should minimize these things, but at the same time, it is important to perform manufacturing sometimes to also save any energy at a larger scale. So, manufacturing is important, but you need to make sure especially when you are dealing with carbon, then you are taking care of all the environmental policies.

Thankfully, we do have a lot of policies related to pollution control, but you need to make sure that you abide by them. And especially if there is anything harmful is being produced or anything that does not seem very harmful, make sure that you take care of the environmental pollution aspects.

Now, in India and all over the world several prominent business players are actually involved in carbon-based manufacturing. Many manufacturers are actually making the raw material for other industries. Let us take an example of tire manufacturing, car tires. So, what are tires? They are made of carbon-reinforced rubber, reinforced means you mix carbon into that rubber for strengthening it. Now, a lot of companies are making this reinforcement material, this type of carbon black, a lot of people are actually involved in carbon black manufacturing.

In fact, India happens to be the 2nd largest producer of carbon black in the world, 1st being China. There are companies that are manufacturing carbon material, but because they are raw materials, they are not final products.

Now, there are some numbers again based on you can do your own internet search and probably you know by the time this lecture reaches you, the numbers have already changed. But the point is that a lot of different carbon materials being produced in India and all over the world.

Some companies will produce more carbon black, some countries will produce more graphite-like carbon, some countries have more production of glass-like carbon. So, there are different countries with different carbon material production. But, the point is that the numbers are large and they are rapidly growing.

Now, all these aerospace applications and car manufacturing and so on, are rather utilizing carbon-based composites rather than you know direct carbon materials. So, what are these carbon-based composites? So, this is what we are now going to learn.

This can be called also next generation manufacturing. Next generation is anything that is too advanced for the time being. So, that is the futuristic applications and include carbon composites.

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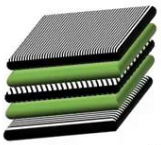
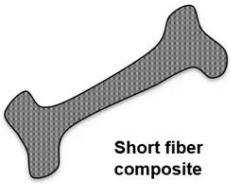
Carbon-based composites

- Composite materials are prepared by mixing two or more chemically and physically distinct materials in the form of a matrix and an additive.
- Carbon structures such as carbon fibers, carbon nanotubes are mixed into polymer matrix directly or as laminates (layer-by-layer).
- Composites feature a high mechanical strength.
- Carbon/ polymer composites can also be converted into carbon/ carbon (C/C) composites.
- Such materials can withstand very high temperatures.
- Many applications of carbon fibers are actually via composite formation.
- Examples: aerospace, biomedical implants, various structural materials/ components.
- C/C composites and hybrids is a rapidly growing industry.
- Recycling of carbon materials including carbon fibers and composites is also challenging.

Laminated composite



Laminated composite



Short fiber composite

So, what are these carbon-based composites? What is a composite in general? As I said that materials can be anything. Now, composite material is yet another thing that you need to understand. Basically, it is a mixture of two or more materials. Now, these materials should be chemically and physically distinct from each other. So, it is not like making an alloy, where you are mixing two metals and forming a solid solution.

The composites are not like solid solutions. So, they are not uniform materials. So, you do have two distinct phases, two distinct materials; this is also a mixture of materials. Typically, you will have something in a form of a matrix and then you add something into the matrix. So, there is one matrix phase and there is an additive phase, together known as a composite material.

There are also some other materials known as hybrid materials, which are more complex or multi-material. They also have complicated structures; they have sometimes sandwich-like structures. These are known as hybrid materials. Hybrids are typically more than two materials and also they can be very different from each other.

So, there also a lot of carbon materials being used for making these hybrids. So, let us talk about composites. What are composites? How do we make composite from carbon fiber? Now first you need to a braid. So, you can basically make this kind of structures when you weave. So, you can prepare these woven carbon fiber mats and these woven carbon fibers are laminated.

So, you take one polymer which is like a binder material, typically a highly viscous polymer and these are known as resin; we will talk about resins a lot. So, you take one layer of these woven carbon fiber mats and then you put some resin and you infuse some resin into it. Then you put another layer and then again infuse some resin into it and then another layer and so on. These kinds of structures are known as laminates.

So, lamination is the layer-by-layer structuring or layer-by-layer manufacturing. So, these kinds of structures, the green color here indicates resin (refer to slides) And, then the black I have shown are carbon fibers. Some are perpendicular some are at a certain angle. If you do this then your overall material becomes stronger and stronger. So, these kinds of materials are known as composites.

And composites can have just short carbon fibers or carbon nanotubes or any carbon structures; not just carbon necessarily, but since we are talking about carbon. So, you can have various fibers mixed inside a polymer matrix, the resin matrix in this case. So, in all these cases your resin is the matrix phase and the additive is the carbon material which is typically carbon fiber.

So, you have these different types of composite materials that are based on carbon. They definitely feature a high mechanical strength. In fact, the very reason for making composite materials is to get high mechanical strength and I have shown this picture that of a bone. So, why did I show a bone? Because this kind of composite materials are nowadays being used for making bone implants.

What does the bone-implant require? It should be biocompatible, means that the material does not really harm your cells. But at the same time, it does not degrade. Now, if it does not degrade, it may not be good for some drug delivery applications. Because when you are doing drug delivery what do you want? You want the drug carrier to degrade and you know they go out of your body. But that will not happen with carbon because of its stability, because of its inertness, it does not really degrade very easily. So, we do not use it for that kind of applications. However, for making a bone implant it is a pretty good material, you do not want your bone to degrade over time anyway.

You do not want your bone to get damaged or get corroded or chemically reacts to your body. So, it does not offer any harm and also these resins that are used in that case, especially for bone implants or any biomedical implants, also are very highly biocompatible. And also they also do not have any harmful effects; so, they are also biocompatible.

The point is that these kinds of carbon-based composites nowadays are very extensively used for the next-generation futuristic application, we have already started doing it. So, these are composite materials, these have very high mechanical strength.

Till now we were talking about the carbon-resin composite, resin is a polymer. Can you also make carbon-carbon composites? Why should we make carbon-carbon composite? Because resin or any polymer would typically not withstand very high or very extreme conditions; these are softer materials and these are hydrocarbons that typically would degrade at higher temperatures.

Let us say if I have 400 or 500 degrees temperature, that will not happen for a bone implant, but it can definitely happen for a turbo engine blade. So in that case you need some materials that can withstand high temperature, but at the same time, they also need to have high mechanical strength. Now, you already know that we can convert polymers into carbon that is how we made our carbon fibers. In fact, what you can do is you can re-carbonize this entire structure or re-carbonize the resin in the composite. Then you will get carbon as the matrix and also carbon as an additive. These types of materials are known as carbon-carbon composites, remember that we are still using the term carbon in this case. So, I told you carbon is not a unique material, but still, now we are just using the term carbon. We are not using the term graphite or anything else.

Also in the case of carbon fiber, we do not call them graphite fiber or diamond fiber, we just call them carbon. So, there is a certain class of carbon materials when we do not completely understand their microstructure or when it includes various types of microstructure. For example, depending upon the heat treatment conditions, you may actually have different carbon fibers with different microstructure. In that case, the more sort of general industrial name is just kept as carbon.

And we do not go into the details of how much graphitic it is and what is the crystallinity of the material, that you will understand when you are making the carbon fiber and when you are going into the manufacturing. Then, what is the crystallinity and how do you get that crystallinity and what are the process parameters, become important? But, in general, the common industrial name is carbon fibers or carbon-carbon composites.

Now, as I said the biggest advantage of carbon-carbon composites is that they can withstand very high temperatures. And, that is where they then become a completely different type of

manufacturing materials. Graphite and a lot of carbons are actually used for making high-temperature materials because temperature stability is very important for carbon.

In one of the coming lectures, we will see the phase diagram of carbon. And, then then you will see at what temperature pressure what kind of crystalline phases can exist in carbon materials. Then, you will see that this element can withstand very high pressure-temperature conditions compared to many others. So, you know graphite does not directly sublimate, it converts into vapour, the liquid carbon phases exist in very extreme conditions. All of these interesting facts, we will learn in the phase diagram of carbon.

So, the point is we use these materials for high-temperature applications and you hear that this aeroplane body part is made of carbon fiber. They are actually carbon fiber composites and not directly carbon fibers. Because if you see this first image, you see this woven carbon fiber mat is difficult to directly use.

Typically even for the weaving of carbon fibers, you often require a little bit of resin just to be able to weave them nicely. And, the laminated composites or short fiber composites are typically what you see everywhere; that is what industrially it is called carbon fiber, but it is actually carbon fiber composite. You can do your own Google search and then you can find out more applications of these carbon-carbon composite materials, carbon fiber composite material and carbon polymer composite materials.

Now if you take one carbon fiber, one carbon nanotube not one but many, then you mix them into the resin matrix. So, this is also a composite in principle, but this is a little more complex. Or, if you give a certain specific shape to your carbon structures, then also you still have the resin and you still have an additive in the matrix, but you may have something little more than that.

So, all of these materials are generally known as hybrid materials, they are used for example, for making wind turbine blades. So, the wind turbine is an interesting application again. So, wind turbines do not require very high-temperature conditions, unlike gas turbines. But, they definitely require lightweight blades and they should not buckle. These are very important parameters for wind turbine blades and a lot of wind turbine blades are still manufactured using glass fiber reinforced plastics, but nowadays carbon fiber reinforced plastics are also used.

So, when you hear carbon fiber reinforced plastics that means carbon fiber is mixed inside a polymer matrix, it can be either very short fiber or laminates. So, CFRP is what you will commonly hear or just carbon fiber. They have interesting manufacturing applications of course.

In the previous slide, I mentioned to you that you should make sure that you are taking care of the environment when you are doing manufacturing with carbon. The same thing again, when it comes to carbon fiber-based manufacturing, it is important that you are able to recycle these carbon fibers. Because this is an advantage of glass fiber, that is why they are used for a lot of applications because they are easier to recycle. In the case of carbon fibers it is slightly more difficult, because of the fact again that carbon is a very stable material, because of the fact that carbon you know does not degrade easily.

So, recycling and melting of carbon are not possible and that is why the reuse and recycling of carbon fibers, as well as carbon-based composites, is relatively more challenging. But, these are all the aspects that you need to take care of when you are doing carbon-based manufacturing. So, from now on we will talk more about carbon materials. But, one thing I hope I was able to convince you that carbon is a very important technological material.

And, for all the engineers, for all the chemists and for everybody who is attending this lecture, carbon is going to be used also for both academic and industrial purposes. So, this is a very important material.