Carbon Materials and Manufacturing
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Lecture - 39
Introduction to Carbon Fiber Reinforced Plastic (CFRP)

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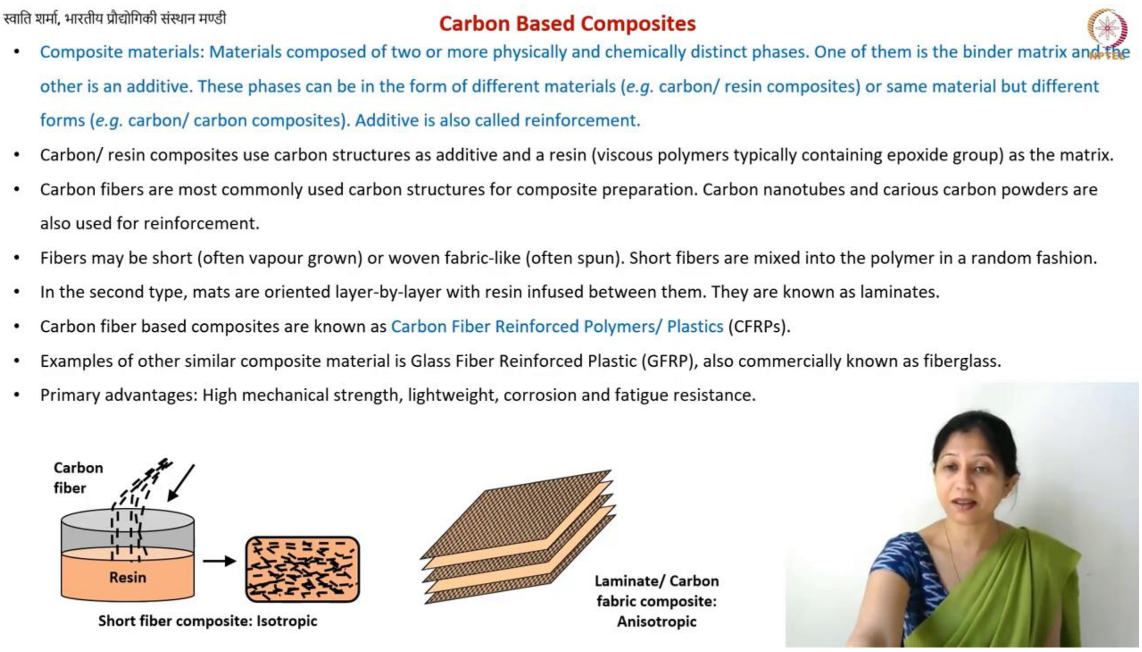

Hello everyone. In this lecture, we are going to talk about some very interesting carbon-based materials, and these are carbon composites. So, you must have heard so many things about carbon-based composites. They are considered the next generation manufacturing materials, they are used for a number of applications because they are lightweight, they are strong and they offer interesting deformation properties, they also can offer certain electrical properties.

Because of all of these properties, they are also replacing the metals for some of the traditional applications. Let us talk about carbon-based composites before that, first we need to understand what is a composite itself. What is the definition? Why do not we call it a mixture?

You read here that composites need to have at least two physically and chemically distinct phases, we put them together and this overall material is called the composite. But how is it different from a mixture? Well there is a certain fashion in which you prepare the composite. You always have one binder phase and one additive. There is some sort of a matrix where you add something, and these two materials are quite different.

When we say that they are physically chemically distinct, this also means that number 1, they do not react with each other. Even if you want to separate these two phases after a very long time after your entire structure has gone through a lot of mechanical deformation or it has experienced a lot of heat, after all the conditions still you should be able to separate these two phases, they should not form chemical compounds.

So, this is also another interesting feature of the composites. So, you have always something added inside a matrix, this additive is typically what carries the mechanical strength and that is why you have often fibers, tubes these kinds of structures as the additive. So, this is the definition of composite materials.

Now, most of the carbon-based composites that are used for manufacturing applications are actually based on carbon fibers because additive should have a good mechanical strength and especially, when carbon fibers are woven like a fabric. So, when you make bundles or yarns out of them, rope like structures out of them and then you do the weaving like a fabric, then you have these very mechanically strong as well as flexible structures.

These structures are then most common for making carbon-based composites. So, how do we do that, this is what we are going to learn in this lecture. You can have carbon and resin-based composites, so you can have your binder phase as a polymer and these polymers are resins.

You already know resins are very viscous, glue-like polymers. They are also sticky and viscous polymers and these polymers also have this interesting property that they can be hardened or they can be cured, so you can use them in the liquid form and afterward you can heat treat them or even sometimes you can just mix two components like if you have ever purchased an epoxy glue, you have two components and when you mix them together, then they crosslink and then they harden. Basically you also have this property of hardening the resins.

These are thick viscous polymers and they can also have different viscosities and they also have different chemical structures, but we will have a resin as matrix and we will have carbon fibers added to it. We can also have carbon fibers added inside other carbon matrix.

So other disordered carbon material is your matrix and carbon fiber are your additive, those kinds of composites are known as carbon-carbon composites, we will talk about them in the next lecture.as I mentioned carbon fibers are most commonly used, but then you still have two different types. You can have either short fibers or you can have long fabric like fibers. Short fibers how do you get? If you remember from our first class on carbon fibers, we discussed that we have two types of carbon fibers, either you prepare them by spinning, melt spinning or electrospinning then you will get long fibers, then you can do weaving with those fibers or make yarns. You also have chemically grown, vapor grown, CVD grown carbon fibers; these fibers are the shorter fibers. These are shorter but you have better graphite content, you have better control over their property, they might have higher electrical conductivity compared to spun fibers. But on the other hand, you can control spun fibers properties and their crystallinity by tuning the heat treatment temperature. So, we have these two types of carbon fibers.

In the case of short fiber-based composites, you typically have vapor grown fibers, but having said that you can also have long fibers and then you cut them into small pieces what you do now is you add these short fibers.

Here in the picture, you can see, you take a resin, you add these short fibers and that is it, and you will get your composite. Now, you cure your material, you give it a certain shape.in the case of all carbon-based fabrication whether we are making something out of graphite or glass-like carbon, we are often molding or shaping or forming the precursor itself and then performing the heat treatment.

Here in this case, we are not performing the heat treatment at this point, we prepared the carbon fibers. If there was any heat treatment required for example, after electro spinning, we performed that already. Sometimes you will not make your own carbon fibers you can just buy carbon fibers, then you do not know whether they are vapor grown or they are spun. You just buy them.

But now, you add these carbon fibers, and you mix them inside the resin and now you shape this entire structure and then, harden or cure your resin and you get a structure that has randomly distributed fibers because you basically mix these short fibers. So, now, you have random orientation of the fiber so, this is more like anisotropic material.

Now, in the second type, you have anisotropy. What does that mean? That means that you have specific properties in one direction, in the parallel and in other two directions you will have very different properties. This already gives you an idea of a layer-by-layer structure similar to graphite. Graphite crystals are also layer-by-layer organized and that is why this material compared to disordered carbons has very high anisotropy.

The same thing happens also in the case of polymer. So, what you have? How do you make them these kinds of composites? You call them laminates; laminates basically mean these structures that are prepared layer-by-layer. You take one layer of your carbon fabric, so it is already woven carbon fiber mass. So, you put this one layer, then you infuse some raisin, then you put some resin on top of that, you can even take a brush and paint the resin on top of this structure or carbon fiber mat.

Now, what will happen? The raisin should go inside your mat, it should infuse inside your carbon fiber mat, then you place another mat, then you place another mat and so on and this is how you at every step, you sort of press it nicely. You make sure that the resin has gone inside your mat and this is how you make these structures. Now, you have this layered structure which will definitely offer very good mechanical strength if you try to break it from the top.

There is this one term that is used for all the carbon fiber-based composites that is known as Carbon Fiber Reinforced Plastics or Polymers so, CFRP. This is the term that you will hear quite a lot. You also have a similar material, I mentioned it because people have to compare the properties of their carbon fiber reinforced plastics with Glass Fiber Reinforced Plastics.so, you will see comparisons between GFRP and CFRP often.

GFRPs are basically similar things, but you have glass fiber. you can also do weaving with glass fibers by the way. The same things that you do with carbon fibers, you can also do that with glass fibers. Glass fibers are typically made by melt spinning and not electrospinning. Now, it is easier to recycle glass fibers, and they are relatively inexpensive compared to carbon fibers because you do not have to perform any heat treatment.

So, there are advantages. However, your carbon fibers offer more strength and improved properties like electrical properties which is not there in the case of glass fibers. However, these two are similar materials. For examples, some very common example of manufacturing using these CFRPs and GFRPs is wind turbine blades. So, wind turbine blades even today are mostly made of glass fibers GFRPs. GFRP also is commercially known as just fiberglass.

The actual technical term is glass fiber reinforce plastic, but people just call it fiberglass. Fiberglass is the more commonly used material for wind turbine blade manufacturing, but carbon fibers can offer better mechanical strength and they might also be lighter, so that is why there is a lot of research going on it. We want to replace GFRP with CFRP.

There are many advantages of course, you already know that you have high mechanical strength, you have lightweight, you have also corrosion resistance because carbon fibers are very inert. So, all the properties that we are actually discussing also in the context of other bulk carbon materials are applicable.one additional thing is flexibility because otherwise our typically your carbon structures are not so flexible. But when you make a fabric, then they also have this flexibility.

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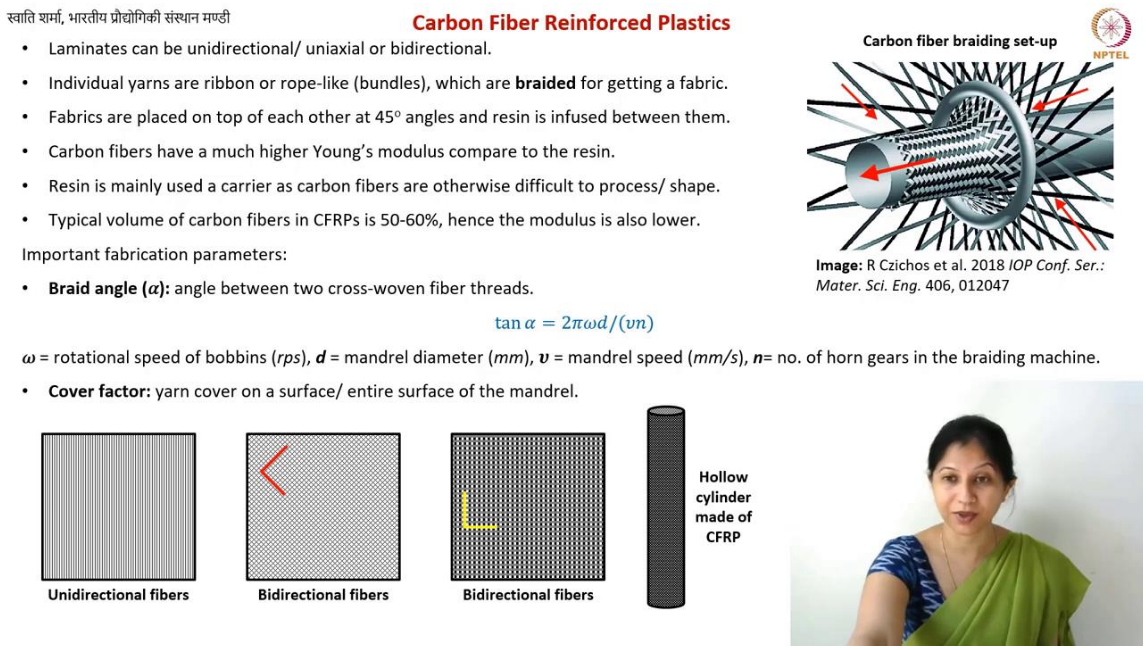

Now, let us talk about the laminate type of structure, the second type. Short fiber composite will give you anisotropic material. What is very important when you are preparing any composite material especially with carbon that you need to understand that your carbon fibers or carbon structures generally have very high surface energy what does that mean?

That means it is really difficult to mix them with anything. So, your the interface between your resin and carbon fiber that becomes very important to you. You want to make sure that there is no air trapped and that you have good adhesion between the two components, but that is where a lot of research is moving towards in that direction where you understand the properties of the interface of these raisins and carbon fibers or any other carbon material.

Let us anyway talk about the laminates. You have two types of laminate structures; they are known as unidirectional or bidirectional or sometimes also uniaxial and biaxial. What does this mean? Unidirectional, as you can see in this picture, you have individual yarns or bundles or threads whatever you want to call them. These bundles are braided in a parallel fashion.

First of all, what is braiding? You can see this image here, you have something known as a braiding setup or braiding machine where you see the red arrows. You feed carbon fibers from different directions and then it is woven like a braid and you see that the entire fiber structure comes out, that is the mat that comes out.

Now, you can have the mat in just parallel fiber yarns, or you can also have them this kind of cross structure. They are braided in such a way that they make a right angle with each other. So, you can have them as a cross. Basically, this cross-like structure is what you have in bidirectional fiber. So, you have basically fibers woven at a 90°angle with each other.

And now in this third image, you see that there is a hollow fiber cylinder. You make the fabric by braiding the carbon fibers and then you place these fabrics and then infuse the resin with different processes. You can make any structure by molding. So, you can have these fancy carbon fiber structures.

When you make laminates, you have unidirectional or bidirectional laminates, but when you place them on top of each other, you will often place them at an angle of 45. Why do you do that? Because then if you have like 10 layers of your carbon fiber and each one of them is sort of rotated by 45° angle, then it can withstand much more mechanical stress. Because the stresses will be distributed through the material and that is why it will not easily break, so that is why you also place these laminates or each fabric whether it is unidirectional or bidirectional, you can place them at the 45° angle from each other.

Now, I think I mentioned it before that it is the additive that carries the mechanical strength. Definitely the mechanical strength of carbon fibers is several times higher than that of the resin, but the density of resin is typically slightly lower than that of carbon fibers.

So they make them lighter, but anyway the difference in density is not so much. The point is that the mechanical strength of the carbon fiber actually reduces when you mix the fibers with the matrix because now you will have 50 to 60 percent carbon fibers in a carbon fiber-based composite.

You also have the 60 percent of Young's modulus that you had if you had measured one yarn of carbon fiber, compared to that you will also have slightly reduced mechanical strength. However, resins are important because without them you will not be able to process your material. Because even if you see this braiding machine, the threads that are the yarns that are going inside the braiding machine, they cannot flow so easily. They will mechanically damage, there will be a lot of friction if we do not have the resin because it also acts as a lubricant and as a binder as well. So, it is important for us to have the resin.

Now, let us talk about the braiding parameters first, then we will also talk about the parameters how we further process these resins. Now, I have not given the details of different components of the braiding machine here, but you can see there are certain holes from where your threads are going inside.

And then, they are being braided that will, of course, depend upon the rotation of your cylindrical structures known as mandrel. So, the rotation of your mandrel and also the speed at which you are feeding the fibers and even these things will also depend on the kind of gears that you have in your machine. So, based on all of these parameters, you define something known as the braid angle.

Here in these images, you see that you have this braid angle which you would like it to be 90°. When you are doing the braiding, you want it to be 90, but what happens is if there are any process parameters which are not perfect, so these are what you will call manufacturing defect if your braid angle is not exactly 90. So, if you get 85 or 95, then that is your manufacturing defect. And that braid angle α is determined by this relationship that I have shown here.

$$tan\alpha = \frac{2\pi\omega d}{\vartheta n}$$

Omega basically is the rotation speed of your bobbins, bobbins are these holes where you feed your thread. In fact, if you have ever performed sewing using a sewing machine, then you know what bobbins are.

So, omega is the rotational speed of bobbins and then, you have the diameter of the mandrel of the cylinder, then the speed of the mandrel and also the number of gears because that will determine the rotation speed. So, basically, your braiding angle depends on all of these parameters and if you are not able to get the exact angle that you wanted, then maybe there is something wrong with one of these parameters.

When you prepare these carbon fiber fabrics, then the other important factor is the cover factor which is defined as the ratio of the yarn cover of the surface and divided by the entire surface, how much surface is covered basically with the fibers.

When you have these kinds of fibers, you do not want to see holes through them. Sometimes there are voids. So, these are the parameters that are important when you are braiding the carbon fibers or making fabrics.

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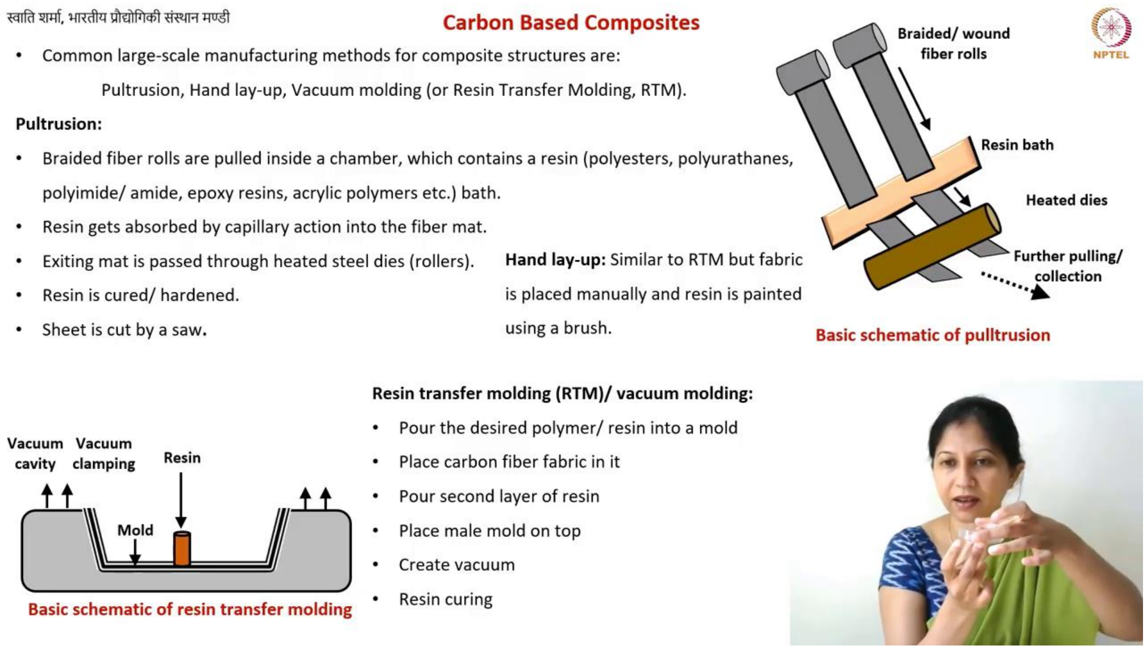

Once you have the fabric, how do you make the large-scale composite structure? As in the case of other carbon materials, the fabrication of the structure is done with the polymer itself rather than with carbon, but here slight difference is that we already have carbonized fibers and then we are giving it a shape.

However, if you want to make carbon-carbon composites, then you then further carbonize these structures. So, you have carbon resin structures and that a lot of resins especially phenol formaldehyde type resins can be converted into carbon so then you further carbonize the entire structure. However, the shaping needs to be done at this stage when you have a flexible structure, when you have the resin mixed into it.

So, how do you make these composite structures specially the laminates? There are three common methods, the first one is known as pultrusion.as the name itself suggests, it is some sort of extrusion, but with pulling and that is why it is called pultrusion. Then, you can also perform what is known as resin transfer molding. So this is a molding process where you keep on filling the resin and you can also do this by hand, in that case you call it hand lay-up.

Let us discuss each one of them. First of all, what is pultrusion? So this is a basic schematic of the pultrusion process. You can see that you have these reels of fibers. When you make your fibers and when you braid your fibers after that you keep on winding them on top of a roll-like structure. So, the fibers themselves rolled on top of a sort of a cylinder.

Now, you have these cylinders, there can be multiple cylinders, I have just shown two. So, you have cylinders and then you keep on pulling the cloth or your fibers and then, they pass through a resin bath. They go inside a certain sort of a pot where you have the resin bath and based on the capillary action, your fabric will take some resin inside and then this entire structure goes through these hot pressing platforms.

Typically, you have rollers made of steel which are also heated. So, you can call them heated dies. basically what is happening is resin is absorbed inside your carbon fibers, it is infused, then your entire structure goes under this rolling heated rollers dies. After that because of the heat from the die, your resin can be thermally cross-linked, then it will be cured and it will be hardened.

If needed you can also perform a little bit of drying afterward that is all. Then you can give it any shave by cutting it using a saw. This kind of fabrication technique will be very useful if you just want to make large sheets of your resin and do not want to give it very complex shapes, in that case pultrusion is useful.

But if you want to give it complicated shapes, then what is most commonly used is resin transfer or vacuum molding.as the name itself suggests you have a vacuum. So, the suction of the resin inside your carbon fibers is done under vacuum.in that case, you can have the resin filled inside very nicely rather than just the capillary forces. You want to make sure that it goes everywhere, and you can also make a mold.

You see in this image, you have certain mold. Let us say you wanted to make this kind of a bucket like structure.in that case, you can already prepare your mold and then you place one sheet of carbon fabric and then you place some resin. Here, you don't do by hand, just pour the resin and you suck it in using a vacuum pump.

So, you can see there is an inlet for the resin and once you have the resin ford inside, then you create the vacuum. You make sure that the resin is infused inside your fabric. Now, you place the second layer, now you place the third layer and every time you create vacuum for filling the resin. This is the resin transfer molding method.

Of course, after everything you will again cure it, harden your resin and then you can take the entire structure out of your mold. These are some of the steps pretty similar to what you do also in terms of chemical process because of the nature of carbon fiber and resin pretty much remains the same. But the only thing is that here you using vacuum too and you also use a mold before you start your process.

And the third thing is hand lay-up. I am not showing the individual steps basically you have pretty much the same process. Here you also have a mold.in fact this is something you can do for yourself at home, you can just take a big plastic mold or a plastic bowl and place one carbon fabric on top of it and then pour some resin let us say acrylic resin. You can purchase in the market, then paint it and using a brush. you can make sure that the resin is infused inside your fabric.

So, you can take a brush paint the resin, then you can again place another layer of carbon fibers, another sheet of the fabric and again, then press it. There is also something known as a male mold and female mold. What does it mean? for example, I have two structures. So, this is if I have this I do not know if it is visible(refer to video at 25:00).

If this is my female mold, I fill resin inside it and then I have something that fits inside in the next round. So, I take one mold, put the raisin and then put the male mold, this is similar to a lot of manufacturing techniques. You use male and female parts of a lot of things.

So, you can also press it using the male mold and then remove it, then you place the second sheet, again paint the resin, press it using the male mold and so on for as many sheets as you want. And then cure the resin, harden it by heat treatment and then, you can remove your entire structure.