Carbon Materials and Manufacturing
Prof. Swati Sharma
Department of Metallurgy and Material Science
Indian Institute of Technology, Mandi

Lecture - 40
Machining of Carbon Fiber Reinforced Plastic

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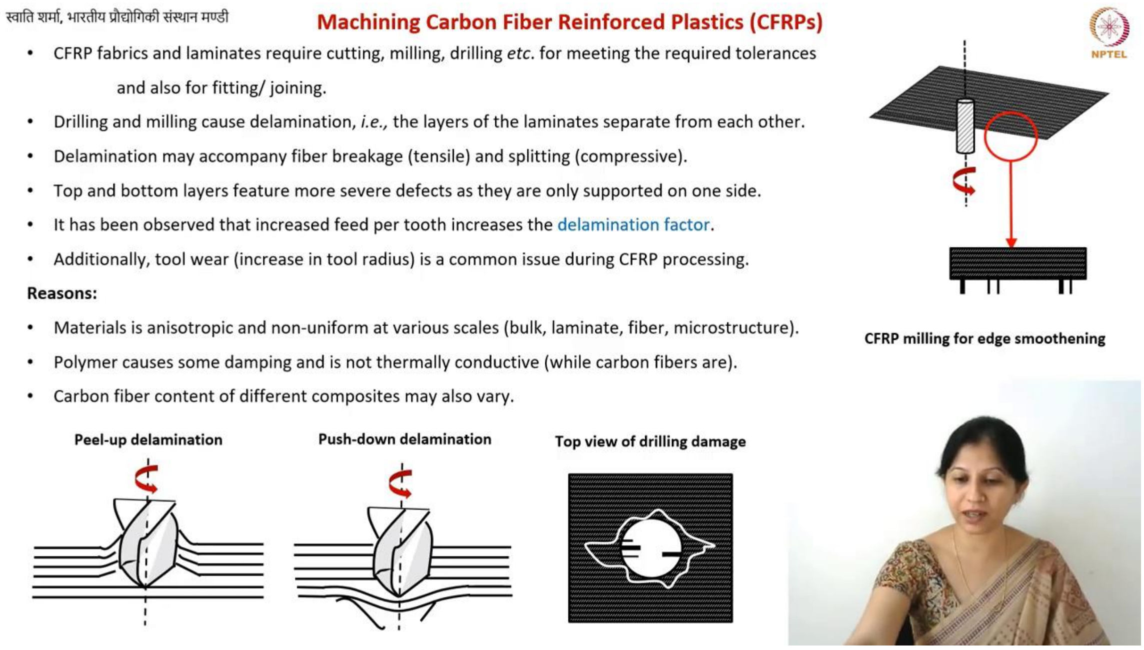

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Machining Carbon Fiber Reinforced Plastics (CFRPs)

- CFRP fabrics and laminates require cutting, milling, drilling *etc.* for meeting the required tolerances and also for fitting/ joining.
- Drilling and milling cause delamination, *i.e.,* the layers of the laminates separate from each other.
- Delamination may accompany fiber breakage (tensile) and splitting (compressive).
- Top and bottom layers feature more severe defects as they are only supported on one side.
- It has been observed that increased feed per tooth increases the delamination factor.
- Additionally, tool wear (increase in tool radius) is a common issue during CFRP processing.

Reasons:

- Materials is anisotropic and non-uniform at various scales (bulk, laminate, fiber, microstructure).
- Polymer causes some damping and is not thermally conductive (while carbon fibers are).
- Carbon fiber content of different composites may also vary.

CFRP milling for edge smoothening

Peel-up delamination

Push-down delamination

Top view of drilling damage

Hello everyone. In this lecture, we are going to discuss how to machine, and what are the problems during Machining of CFRPs or Carbon Fiber Reinforced Plastics Reinforced Polymers. So, we have two types of CFRPs, we learnt in our previous lecture. One that is made of short carbon fibers.

And these short fibers can be either vapour grown carbon fibers or they are actually spun fibers, they are long, but we have cut them into smaller pieces. The other type is laminate. So, we already learnt how to work with laminates, and how do we make structures. We take a big mold, we place the sheet of carbon fabric in that case, and then we infuse resin, we put another sheet of the fabric reinforce resin and so on. So, this is how you get your structures.

In the case of short fiber-based CFRPs, you can use direct molding. So, you make a mold of whatever shape you need, and then you fill in your resin. Now here one advantage is that this is more or less a uniform-looking material, it is not unlike laminates.

There you have completely different fabric like sheets, but here you can treat it as one material. In fact, this is also true for carbon nanotube reinforced plastics that you can treat them as one material. And then you place the entire or you pour the material inside the mold, and then perform the curing of the resin and that is how you get your structure.

Another option, if you want to get high-quality structures for example, you want to make a bone implant, and you want the implant to be exactly of the shape of the bone that person requires, in that case, you can perform something like 3D printing. So, you can perform a little more advanced techniques in that case. So, this is how you make your CFRP structure.

But after making it, you require certain finishing operations. You also require certain joining operations because you do not just make the structures, but you also attach them to something. For example, if I make a very massive, large wind turbine blade using carbon using a CFRP, then what do I need to do? Afterward, I need to attach these blades onto the tower of your wind turbine right.

I also may have to perform the finishing operation because when we make the mold and we place our laminate, but the edges are not perfect. We know that we will always have slightly extra edges especially when we are doing this layup.

So, in that case, we need to remove these edges. So, we need to perform operations like drilling, we need to perform milling, edge milling, cutting and also all sorts of finishing operations. So, what is the problem when we do this? Our composite materials are different from traditional materials that we know.

So, it is not like metals where you already have all the standards. This is also another challenge, so this is still a relatively new field. You do not have all these standards for your operations. So, you need to optimize. And you need to understand that you have these thread-like structures that can peel off; not each individual rope has the exact same mechanical property or adhesion to the resin.

So, because of this we will have some challenges or some issues. Let us see what these issues are. The first and foremost problem in the case of laminates is the delamination. What is delamination? Laminates are like these layer by layer structures. When the top layer peels off from your bottom layer that is known as delamination of the structures. This is the biggest problem whenever you perform drilling or any operation.

So, for example, here I have shown one sheet of CFRP, and then you have a tool that is rotating, and then performing the edge milling. Now, what will happen in this case? Afterward if you see your finished product, then if you zoom it in, then you will see at the edges you still had these fibers hanging outside.

These were the fibers that at some point got detached from the surface or got delaminated, and that is why they were then sort of flapping, then you were not able to nicely cut them. So, this is one major problem that is very different from any traditional manufacturing material, that is very specific to the laminates.

Now, the delamination is further divided into two types. One is known as the peel-up delamination.in this case, you see there is a drill bit and that is rotating. Along its twists, some material kind of gets attached to it that is known as the peel-up delamination.

On the other hand, the more common delamination is what is known as the push-down delamination, now your drill bit goes inside and then you can see that some bottom layer that got remove, that got detached from its the previous layer, and also this kind of delamination then can lead to fiber breakage. So, these are the two types of delamination.

If I take the top view of this push-down, then you will see that you were able to drill the hole, but you did have some fibers that are not removed. So, some residual fibers you will always see. Why did that happen? Because these fibers were delaminated at some points.

This affected zone or let us call it damaged zone that is often more prominent in the direction of your fibers perpendicular to it. You will still have some damage, but more delamination, obviously, you can see that your fibers are like that. So, when they peel off, they will peel off like this right (refer to video at 6:10).

However, some fibers in sideways will also get affected. But in the direction of your fibers, you will have a more prominent effect. So, the damaged area will look like this what I have shown here. Also the most affected layers from your delamination are your top layer and bottom layer, because these layers are only supported on one side,.the other layers had some support on both sides. So, they are not affected that badly.

Now, this fiber breakage, you can say in this case it is tensile, but you can also have compressive damage. So, the fibers can go away, they can move away from each other. So, you have some compressive damage, but the more common damage your delamination is due to tensile damage fine.

Now, how do we quantify it? As I mentioned already, there are not so many standards in the case of composite materials. And in fact, this is a lot of studies are going on in this direction right now. As in the case of metals, where you already have all kinds of standards.

However, we do have something known as a delamination factor. And delamination factor as by the name you can understand that how much material is delaminating and what is the region that is affected by delamination. It is a measure of that and in a while, we are going to talk about this in detail.

But before that, few more problems which are associated with machining or drilling. You can also have tool wear. So, tool wear is a problem in a lot of machining operations right. This is a very common problem in the case of CFRPs, because you can see that you have a very non-uniform structure. So, it is common that the radius of your tool increases. So, tool wear is also one common problem.

There are also some issues with the finishing operation. So, we will be talking about them. What are the reasons first of all? As I mentioned already your material is very non-uniform. What, do I mean by non-uniform? You have two completely different materials in one material, now you call the composite material.

So, you have your carbon fibers that offer a much higher mechanical strength, they are also thermally conductive. But on the other hand, your resin is not thermally conductive, it also has completely different properties.it has a different degradation point compared to carbon fibers which do not degrade even at very high temperatures.

So the mechanical properties are from carbon fibers and the binding properties are from the resins, so you have completely different materials, that is number 1. This is anisotropic material because you have laminates; you have properties different perpendicular to the plane and in plane. So, this is a highly anisotropic material. This is one problem.

When we talk about the non-uniformity of these composites, it is at different scales.in bulk scale I was just telling you that you have one carbon fiber sheet, and then you have a resin sheet that is when we are talking about the bulk.

However, when we even talk about a laminate structure, then not all fiber bundles are exactly of the same size. You may also have some twisting and entanglement of the fibers or some weak points within your fabric, that is possible, so that is also then non-uniformity.

If you think of individual fibers as I mentioned, the entire fiber diameter may not be uniform, you may have certain bulges somewhere, you may have necking somewhere. If I look inside the fiber, if I look at the microstructure of fiber, even there not each fiber is uniform.

Or even within one fiber, if you see the microstructure, you may have void trapped somewhere, which may cause weak points or you may have turbo static structure, but at some points you may have some graphitic regions. Even within the fiber so you see this is a non-uniform material that we are dealing with.

So, there is definitely a high possibility. It is very difficult to set uniform manufacturing parameters for all parts of your composite. Now, because we have two materials as I already mentioned, the thermal properties of the polymer and the carbon fiber are very different. So, if you have certain heat generated in the process which is always the case whenever you are performing high-speed operations like any kind of drilling and milling, you will have certain heat generated.

Now, in the case of metals, what is the thermal conductivity of your metal and you choose your coolant accordingly, or you also choose your machining parameters of the speed of your drill. You can choose everything accordingly. But here we have two materials.

Carbon fibers have a very high thermal conductivity, but your plastic does not have a very high thermal conductivity, and in fact, it will degrade. It has very low thermal conductivity and it may get degrade at a certain temperature. Or the temperature will go above its glass transition temperature in that case it will start to deform. So, this is one problem.

What else can you think of? The content of carbon fibers in various composites may also vary. So, the most common content is 60 percent of carbon fibers in a CFRP, but this may also vary slightly. And depending upon short fiber-based composites or laminate-based composites, you may not be able to use the exact same parameters in all cases for all composites.

So, these are some of the common problems. Now, let us see how do we quantify these, how do we quantify these properties.

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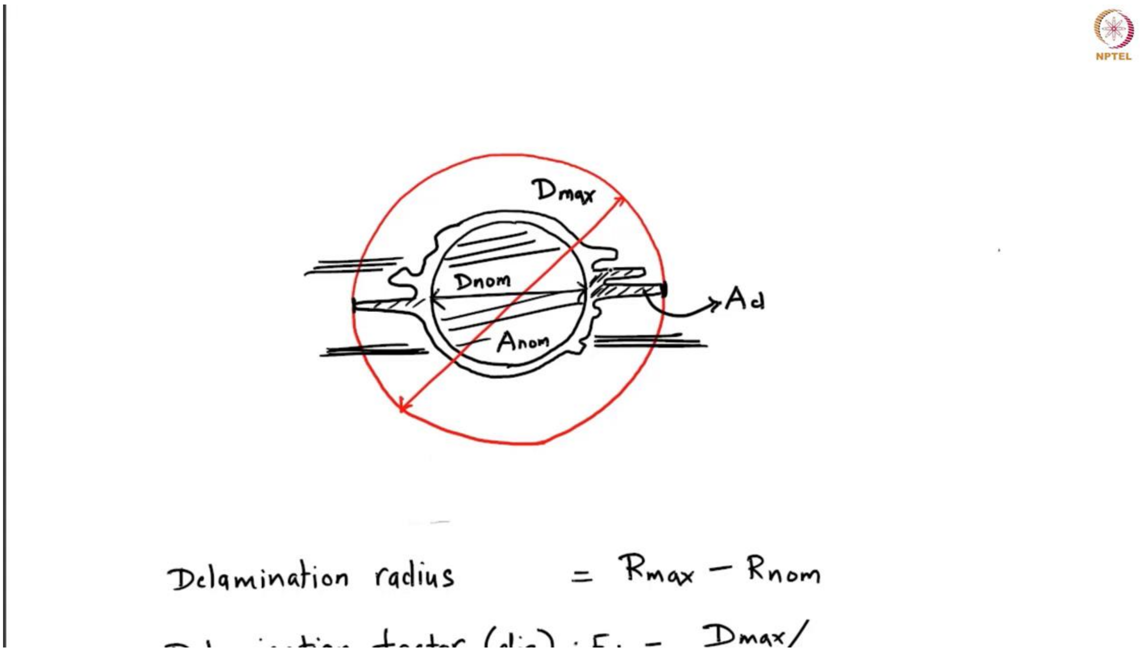

Delamination radius = $R_{max} - R_{nom}$

$D_{max}/$

How do we calculate the delamination factor? So, I had drawn a couple of circles here. This image you can actually relate to what you have seen in the slides. So, the smaller circle here. The inner circle that is the size of the hole that you would like to drill. So, the area of this hole is A nominal or the circle, and then the diameter of the circle the smaller one is D nominal.

Now, you see that there is some damage here; this is your damaged or delaminated area. Why is it like this? Because your fibers are in this direction. So, these are your fibers.in the direction of fibers you are going to have larger regions of delamination and that is why this entire area what I will call this area Ad.

And now I draw one larger circle where I take the maximum delamination. So, now, this larger circle which I have shown with red colour, the diameter of this large circle is what I call Dmax. I am not saying this is D delamination diameter of the delaminated region, because the area is taken only for the actual delaminated region not for the entire bigger circle, but the diameter is taken for the big circle. So, now, I have some of these parameters. And now what I can calculate is the delamination factor.

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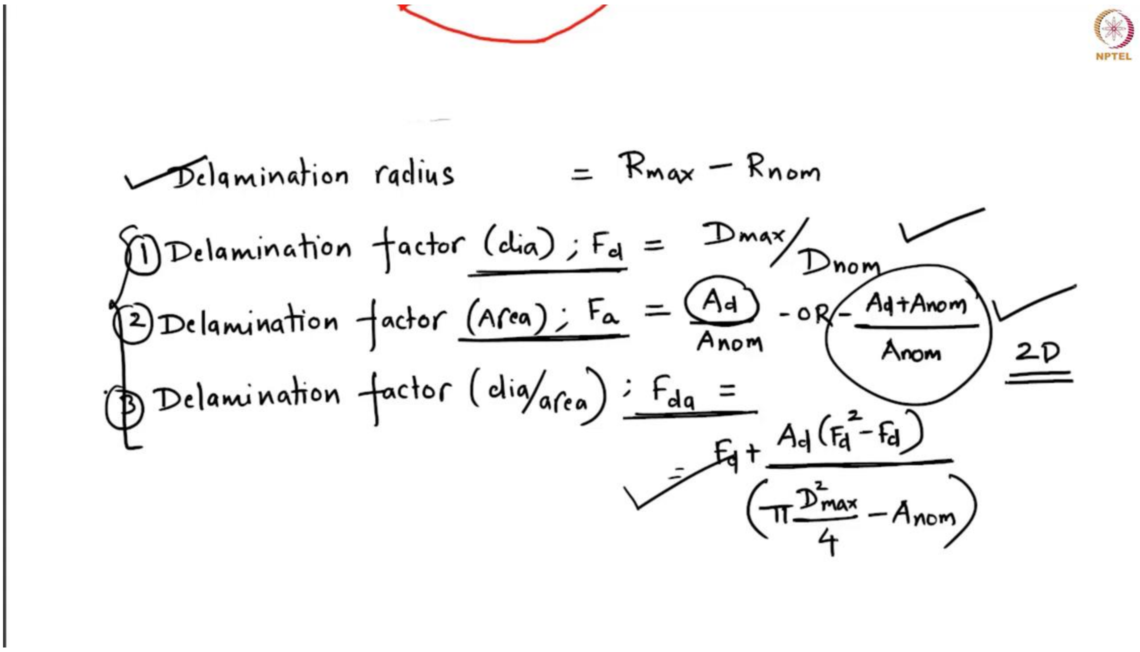

✓ Delamination radius $= R_{max} - R_{nom}$

① Delamination factor (dia) ; $F_d = D_{max} / D_{nom}$ ✓

② Delamination factor (Area) ; $F_a = \frac{A_d}{A_{nom}}$ - OR - $\frac{A_d + A_{nom}}{A_{nom}}$ ✓ 2D

③ Delamination factor (dia/area) ; $F_{da} =$

✓ $= F_d + \frac{A_d (F_d^2 - F_d)}{\left(\pi \frac{D_{max}^2}{4} - A_{nom}\right)}$

Now, there are there is still a lot of work going on in this direction because as I already mentioned that unlike traditional materials, you do not really have all the set parameters for composite material manufacturing that is why we do calculate this delamination factor in many different ways.

However, in any case, one of these factors should be used when you are doing your manufacturing or when you are drilling a hole. Now, first of all how do we calculate the radius of delamination? This is very easy, this is where you will take the larger circle and the smaller circle, and here you can also actually calculate delamination diameter but you will rather calculate the half of it, so delamination radius.

$$Delamination\ radius = R_{max} - R_{nom}$$

Now, delamination factor as I mentioned can be calculate in many ways. First of all we just calculated based on the diameters. In that case

$$F_d = \frac{D_{max}}{D_{nom}}$$

You can also calculate this based on the area.

$$F_a = \frac{A_d}{A_{nom}}\ or \frac{A + A_{nom}}{A_{nom}}$$

And in most cases, this is the one that gives you very accurate values because here you are not calculating as I said the bigger circle.

It might be so that only one strand or one yarn of the fiber that damaged for a large distance but the other fibers did not damage at all. So, diameter may not give you the best values or the idea of what is happening, but area may give you the exact values, but at the same time it is more difficult to calculate the area compared to the diameter.

Now, you can also again even within the area-based delamination factor, you have two ways. You can also calculate it using this second type of formula where you are sort of normalizing it. So, another third way that has been proposed and in a couple of publications you can find it that is using both area as well as the diameter. So, I have written it down here in the slide.

So, this is how you calculate your delamination factor. This is an adjusted delamination factor. Also, you can give different names, for example, the second one the area based, you can call it 2D delamination factor because you are calculating the area and not just the direction. But the first one the delamination based on diameter this is the most conventional one. So, you have these three ways of calculating.

However, you can already see that just if somebody gives you the value of the delamination factor, from that you may not be able to actually calculate the the actual damage. Sometimes also completely different looking areas may have the same delamination factor or as I said that even if you have one long strand that is delaminated, then then the diameter based delamination factor can give you different values for different kind of delamination.

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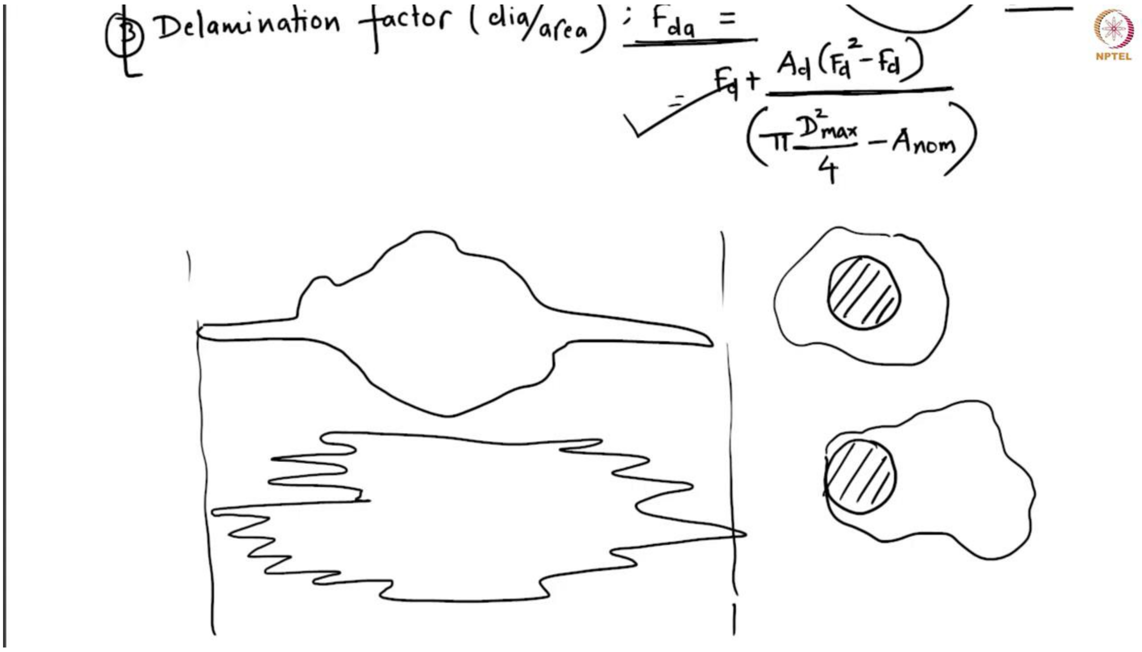

③ Delamination factor (dia/area) ; $F_{da} =$

$$= F_d + \frac{A_d\left(F_d^2 - F_d\right)}{\left(\pi \frac{D_{max}^2}{4} - A_{nom}\right)}$$

So, for example, if there is some structure where the delamination is like this, and then in some cases the delamination although the maximum value remains the same. The delamination can actually be of a very severe nature. So, if I calculate the diameter based delamination factor; because I am just calculating the diameter of the maximum of the bigger circle, then it will still give me the same value.

Similar things can also happen to area-based delamination factor. Let us say this is my hole that I wanted to drill. But also in some cases this delamination the shapes may be very strange, and also the region where the delamination took place that may be different, but still you may get the same delamination factor. However, these are some of the fundamental ways of some fundamental manufacturing parameters for composite drilling.

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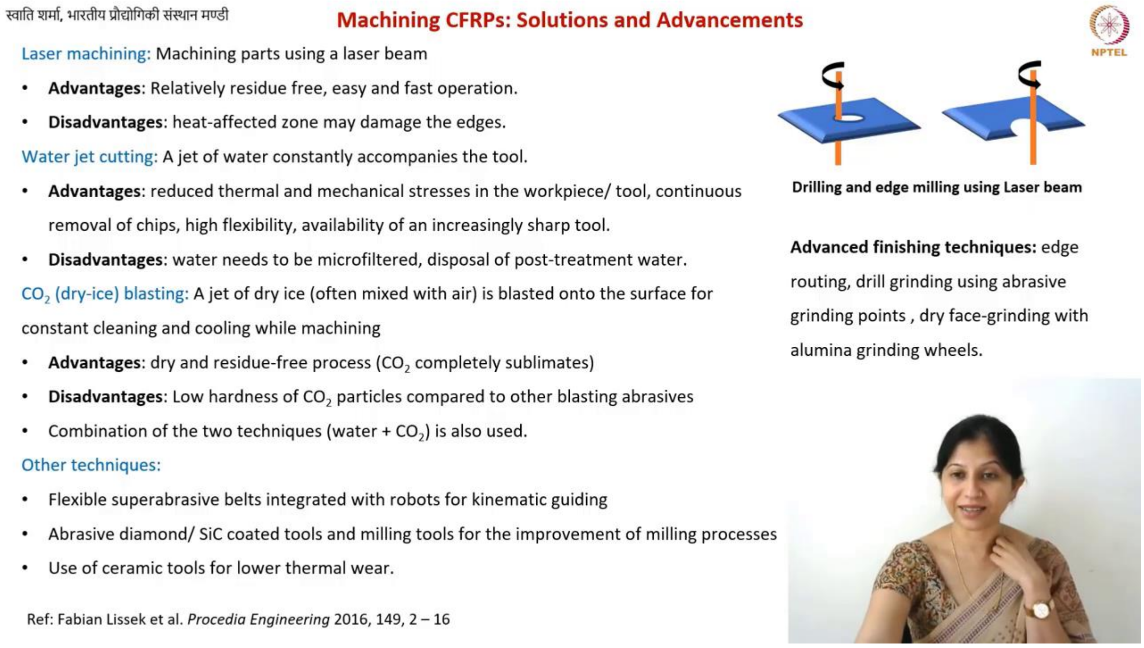

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Machining CFRPs: Solutions and Advancements

Laser machining: Machining parts using a laser beam

- **Advantages**: Relatively residue free, easy and fast operation.
- **Disadvantages**: heat-affected zone may damage the edges.

Water jet cutting: A jet of water constantly accompanies the tool.

- **Advantages**: reduced thermal and mechanical stresses in the workpiece/ tool, continuous removal of chips, high flexibility, availability of an increasingly sharp tool.
- **Disadvantages**: water needs to be microfiltered, disposal of post-treatment water.

CO_2 (dry-ice) blasting: A jet of dry ice (often mixed with air) is blasted onto the surface for constant cleaning and cooling while machining

- **Advantages**: dry and residue-free process (CO_2 completely sublimates)
- **Disadvantages**: Low hardness of CO_2 particles compared to other blasting abrasives
- Combination of the two techniques (water + CO_2) is also used.

Other techniques:

- Flexible superabrasive belts integrated with robots for kinematic guiding
- Abrasive diamond/ SiC coated tools and milling tools for the improvement of milling processes
- Use of ceramic tools for lower thermal wear.

Ref: Fabian Lissek et al. *Procedia Engineering* 2016, 149, 2 – 16

Drilling and edge milling using Laser beam

Advanced finishing techniques: edge routing, drill grinding using abrasive grinding points , dry face-grinding with alumina grinding wheels.

Now, we talk about the potential solutions or the advancements in the techniques that can be used now. First instead of traditional manufacturing techniques how can we modify them to get what is suitable for our composite material. So, number 1 – laser machining, this is very commonly used for carbon fiber or CFRP manufacturing because we use industrial lasers for cutting, for example, PMA sheets.

We use CO2 laser, the IR laser for cutting plastic sheets. Similar lasers can also be used for cutting CFRPs. You can make holes using lasers, you can do edge milling and all kinds of operations. That is one very common technique which is used for machining CFRPs.

What are the advantages? Nowadays laser machining is very commonly available technique in industry. This is also relatively residual-free, and it is a relatively fast operation. So, these are some of the advantages. However, you also have the disadvantage of getting these heat-affected zones. when you are cutting something with laser, you are melting the material, you are actually generating heat. And again I told you that thermal properties of your plastic and carbon fibers are very different. So, it is difficult to optimize the laser parameter to cut the entire structure uniformly.

And if you go to certain laser parameters that are required for removing the carbon fiber that might be too harsh for the polymer, for the resin. And you may end up degrading some of it. So, you will have what is known as a heat-affected zone, that is a common problem with laser machining. You will see it in CFRPs.

What else can we do? You can use common drills or standard drill bits, and we perform the same operation. However, what we have is a water jet that is associated with it. What does a water jet do? Number 1 – it performs cooling; and number 2 – it also removes all the debris, so all the chips that are being produced.it does apply certain force. So, your cutting is relatively uniform. So, certain pressure is also applied by the water jet.

So, what are the advantages? What can you think of? Well, you have reduced mechanical as well as thermal stresses because of the jet of the water.it is not just for the workpiece this cools down the tool. Your tool is typically a metal tool.

So, a water jet that really helps in resharpening of the tool and to prevent the tool wear, this is very helpful. And you also have high flexibility while using a water jet. You can use it in any direction; you can use it in any way. And your tool does not damage that much compared to other techniques.

Disadvantages; the water needs to be micro-filtered. So, it should be very clean because if your water has any kind of particles that can actually damage your operation or that can then act as an abrasive which you do not want. If you want abrasive, then you have well-controlled abrasive where you also control the particle size and so on.

But in this particular case if you are using a water jet, then you need to perform microfiltration of water, that can be relatively expensive and sort of unnecessary. What else? Your water will carry now all the chips that were generated, so the disposal of that water and the post-treatment of that water is also expensive.

So, these are the things that maybe you can use rather at labscale, but when we are talking about industrial-scale manufacturing then the cost becomes very important. So, in that case, water jet has some problem or the post treatment that water becomes an issue.

What else do we do? We can also use carbon dioxide blasting or which is commonly known as dry ice blasting. Dry ice is already solidified carbon dioxide, and now we have a jet of this dry ice during our process. So, this is often mixed with air.

And you have a very high-pressure jet of dry ice that is blasted onto the surface which will perform cooling, which will also perform the cleaning of the surface very similar to what we did in the case of water. So, during drilling, you can also have this dry ice jet.

What are the advantages? There is an advantage that your carbon dioxide is going to completely sublimates. So, it is going to disappear. You are not going to have any residual on top of your surface. In the case of water jet, after you finish your operation, you also have to dry your materials. Of course, a little bit of residual water is going to stay there, but that is not the case with carbon dioxide. So, you get a clean surface. You do not need to worry about it very much. This is residue free process. But there are also disadvantages. Now, you cannot really do machining with carbon dioxide particles. They have very low hardness and also they sublimate reasonably fast.

So, they cannot work as abrasives. Why are we talking about abrasives by the way? We already have a drilling tool. So, why are we talking about abrasive? Abrasive is always giving you a good finish. So, for polishing operations, you will often perform like filing or in the case of larger structures instead of filing, you will have an abrasive – you rub it with an abrasive.

So, this is why good finish abrasives are always helpful. And in fact, we will now learn how can we use abrasive in this case. Often what is used is a combination of water and CO2 jet. So, this is a good balance, in some cases people have used it. And this is useful and it seems that it yields better shapes of your structures.

So, now other techniques, what else? So, these are some of the new techniques which I have just picked up from some of the papers. So, I am not sure if they are already being used at an industrial scale, but definitely, these techniques have been proven to work.

So, you can have these flexible super abrasive belts. So, if you have a belt which contains abrasive particles. This is probably used at an industrial scale, at least a few companies are using it. So, they have these completely automated systems. So, they attach these belts or they provide these belts to the robots. Basically, you have these completely automated abrasions using abrasive or super abrasive belts.

How do they make these super abrasive belts? Well, one option is to coat these belts with diamond particles. And these are chemical vapour deposition grown, CVD grown diamonds. Other particle super abrasive particle is also silicon carbide. Silicon carbon and diamond are two of the hardest materials.

Industrially, they are used for often for making all sorts of abrasives and tools or the tips of the tools, or often the tools have a coating of these kinds of CVD diamond or silicon carbide that prevents the tool wear, and also it provides a better finish to your workpiece. So, when we talk about CVD of carbon nanomaterials, then we will also discuss how can we prepare diamonds using CVD.

Yeah, another thing is that you can use ceramic tools for example alumina, they are also well-known and they have low thermal wear. So, tool wear is less in the case of ceramics, and they do not lose their sharpness. So, you can use ceramic tools. So, these are some of the other techniques which here and there are also probably used in industry, but definitely at lab scale they are used.

What other things can you do for advanced finishing? These are some of the names that I have mentioned here edge routing, drill grinding, and often you will use abrasives in all these cases, and abrasives can be ceramic particles such as alumina, silicon carbides, or you can have the CVD diamond.

For further reading, there are a lot of books on machining of composite materials or just preparation or manufacturing with carbon materials. There is one publication that I have mentioned here; I have taken some of these information from this paper. So, you can also read that.