Manufacturing of Composites
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Lecture – 24
Machining of Composites

Welcome back today we will move to lecture number 24. In this lecture we will try to talk about Machining of Composites. Machining is a subtractive process here we would try to remove the unwanted material so that we try to maintain the required shape and dimension for the finished part. Though composites are set to be near net shape manufacturing, but still when you think of a large component a large part where and which it has to be made by several small part and assembly or when you are trying to do an assembly, but; that means, to say a male part female part and assembly a press fit if you are trying to do then machining comes in a big way. Machining of composites is always a challenge why because the composite material is heterogeneous in nature it has a matrix and it has a reinforcing agent matrix is soft reinforcing is hard. So, we would now try to focus on machining of composite materials.

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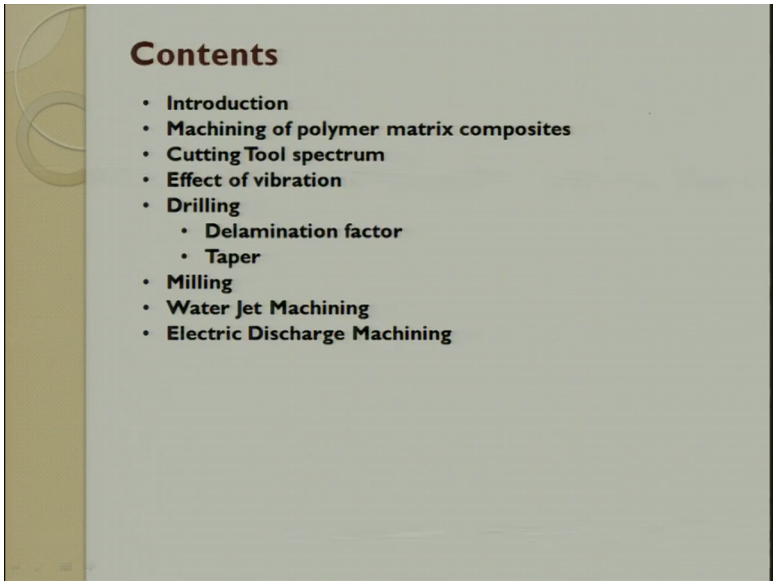

Again here I would like to cover all the spectrum; that means, to say polymer matrix, metal matrix and ceramic matrix composites.

In this lecture first we will have the introduction then machining of polymer composites, then cutting tool spectrum, then effect of vibration, drilling, where and which we have delamination and taper then we will talk about milling water jet machining and electric discharge machining these are some of the processes.

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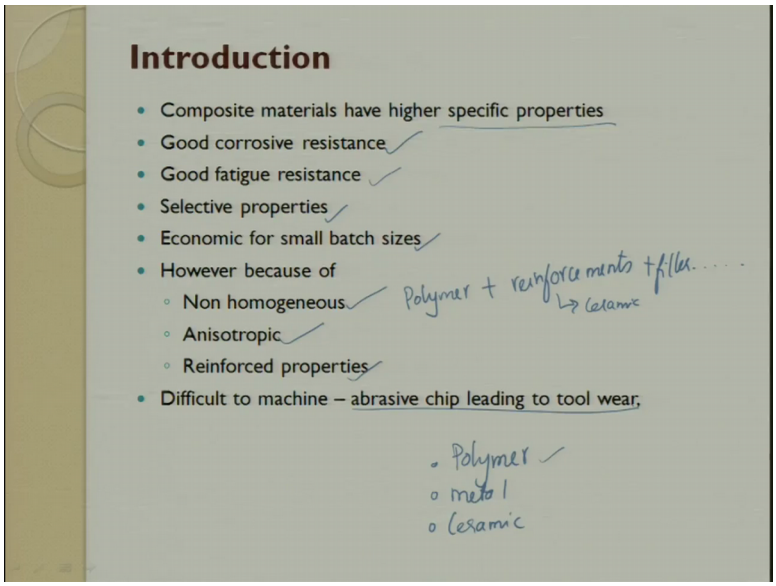

So, when you want to classify machining process we classified into 2 things; one is called as Contact Machining, the another one is called as Non Contact Machining. So, in contact machining there is always a tool which comes in contact with a workpiece, moment there is a tool which comes in contact with a workpiece the tool has to be harder than the workpiece. You the geometry is given to the tool which will have a relative motion between the tool and the workpiece to create any feature of your choice.

So, the examples of contact machining are drilling, milling, turning, boring, grinding these are some of the examples. When you look at non contact machining; non contact machining means there is no contact between the workpiece and the tool. So, here the tools which are used are electrons, ions, photons, and you can also use loose abrasives. So, examples are EDM processes Electric Discharge Machining process, Chemical Machining Process or Electrochemical Machining Process, Laser Machining Process, Ion Beam Machining Process, Electron Machining Process these are some of the processes which are available for machining of composites. You have to make a choice of choosing in this big spectrum which machining process to choose, the simple difference between

contact and noncontact is there is a tool the tool has to be harder than the workpiece that is first difference in non contact it is not.

So, the second differences is moment there is a tool in contact with a workpiece, the material removal rate is going to be high in the non contact since the electrons ions and photons are very small, the amount of material removal rate is very low.

The third one is the thermal damage to the composite is not there in the conventional processes, but where as in the non conventional process there is always a heat affected zone in the composites, with that definition let us get into composite materials have very high specific properties right I am more focus see in the 3 spectrum of composites like; we have polymer matrix, we have metal matrix, and we have ceramic matrix.

So, in this the polymer matrix is always playing a major role because it has a predominant presence in the environment today. So, our focus will be more towards polymer metal matrix polymer matrix machining followed by metal and followed by ceramics.

So, when we discuss about polymer it has a good corrosion resistance, it has good fatigue resistance you can make it anisotropic in nature it is economical when it is a small batch quantity; however, there is a non homogenous; that means, to say there is a polymer and there is a and there is a reinforcement. And apart from that you have other additives like filler etcetera, which they are non homogenous in nature non homogenous in nature why am I reemphasising this because see assignment or tool comes in contact with the workpiece. If it comes to a matrix matrix are always soft and then moment it hits against the reinforcement which is maybe a glass fibre, carbon fibre, kevlar fibre, they are tougher they there stiffer then the polymer matrix.

So, the amount of resistance given by the reinforcement to the tool is high and them. So, the tool has to apply more energy to move further or what happens is the reinforcement tries to obstruct and because of the obstruction the chip flow will not happen so easily so that is a problem, and since it is mixture of materials non homogenous polymer and reinforcement the chips which is produced in during machining will pre dominantly be discontinuous chip.

So, discontinuous chip in this where the volume fraction of reinforcement decide so you will have powdery like structure and since the reinforcement agent are predominantly ceramics the small powders of ceramics when they come in contact with the tool, they tried to create a third body abbreviation in the presence of very high temperature because in contact machining there is going to be a friction factor very dominant, that is why we see when you choose a tool we should have a tool which has high hot hardness, high toughness, and it should withstand, it should be able to withstand very high temperatures. So, that is what we say hot hardness behaviour of the tool has to be very good.

So, here the friction is coming and when the friction is coming the temperature is going to go high, when the temperature goes high there is going to be a change in the shape and at very high temperature when the tool get soften the reinforcing agent when it comes to 3 body abbreviation then there is going to be scratches and the toolbar is going to be more dominant. And an Anisotropic also goes by the same justification the Reinforcement all the 3 properties all lead to non homogenous; because of the non homogenous anisotropic and reinforcement properties the chip which is produced is always abrasive in nature. Generally what happens in metal machining there will be 60 70 percent of the temperature which is taken away by the tool.

But in this case when we talk about polymer; polymer metal matrix composite the polymer will not take any heat. So, the entire heat has to be taken only by the tool. So, basically all the heat goes to the tool workpiece take 0 heat plus, there is going to be lot of friction, and there is going to this all temperature rises the geometry tool rises the temperature of the tool. So, tool softening becomes predominant then now a soften environment and the reinforcing which is trying to create lot of friction there friction and abbreviation. So, it is going to have a catastrophic failure in this polymer metal matrix composites. So, this is a challenge. So, that is why people always look for a proper choice of tool while machining polymer metal matrix composites.

So, this is a classification you have to re look into the classification because moment you are choosing a process you have to understand what is the reinforcing? What is the polymer? What is the temperature?

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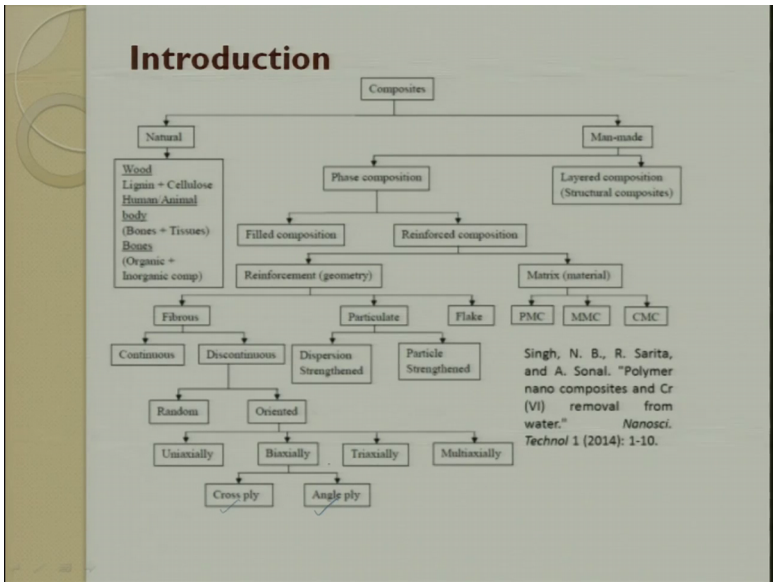

So, composites are divided into 2 classifications one is called as Natural, other one is called as Man-made; in manmade we have phase composition and we have layered composition, phase competition will have filled composition and will have reinforced composition. In the reinforced composition you have reinforcement with respect to geometry and you will have a matrix material coming into existence. When we talked about matrix there are 3 types of matrix polymer matrix, metal matrix, and ceramic matrix. When we talk about reinforcement you have a fibrous reinforcement, you have a particulate reinforcement you have flakes.

When we talk about fibrous they are continuous discontinuous fibre and when I talk about phase particulates it is dispersion strengthening or particulate strengthening. So, there are 2 types of mechanisms which are used for particulate type. Then when it talks about discontinuous I talk about random and I talk about orientation. So, in discontinuous I can I can have random and I can also have oriented when I talk about oriented it will be uniaxial, biaxial, triaxial, and multiaxial. This is a continuous row I mean to say or a rowing and this is discontinuous with this I tried to make a uniaxial, biaxial, triaxial or multiaxial. When I say biaxial it can have an angle ply or it can have a cross ply.

So, when you look into this now it is becoming very clear suppose if I use a particulate type reinforcement these particulates are basically ceramic material. So, this ceramic

material is going to make a friction between the tool and the workpiece. So, this has a higher affect same way when you talk about fibrous glass, ceramic material glass fibre ceramic material. So, here and on top of it to reduce the temperature why can not I used lot of coolant coolant M Q value you can try that is minimum quantity lubricant or you can do flood you can do spray whatever you want to do you do, but you should have a back of your mind polymer is hygroscopic in nature moment it is hygroscopic in nature the polymer is going to attract the O H, moment there is O H present for a for certain duration of time this will try to weakened the matrix. So, you cannot tool also by using coolant. So, these are the challenges.

But whereas, when you use natural fibre and when you use a reinforcement like natural fibre discontinuous or say for example, uniaxial or biaxial if you do jute mat if I used here the aberration action is going to be slightly less and these when the fibre gets cut chopped off into small chips. So, powdery chips these chips some of these chips can also act as lubricant during the process.

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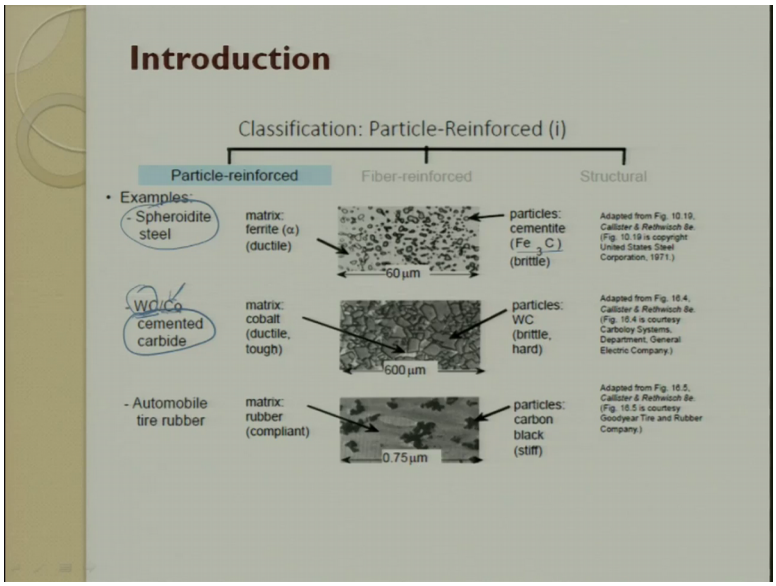

So, the friction and the tool wear is in are to some extent suppressed when you use natural fibre reinforcement, when we look at the particulate type fibre we have seen it in big way.

So, let us look at particulate type so in particulate type for example, in Spheroidite steel you see matrix, which is a ferrite you have and then you have Fe 3 C which is a brittle

material which is hard is getting reinforced such that the properties are enhanced. The next one is tungsten carbide cobalt. So, we see the these are the tungsten carbide particles which are present, which are hard, and we have cobalt, which is a metal, which is getting infiltrated and you make a composite. Then when you take a rubber; rubber is also a rubber tyre which is also a composite. So, these are matrix which is rubber and then these are particulates of carbon which are getting reinforced for several applications. So, you can see very clearly matrix and you can see the reinforcing agent here the reinforcing agent is quite high. So, the tungsten is quite high.

So, nowadays this tungsten carbide cobalt cemented carbide is a good example for a cutting tool, nowadays they are trying to remove this cobalt itself and do a sintering of a completely with tungsten carbide so, but you need to have very high pressure and temperature for doing this. So, these are some of the things. So, I am just put all the figures so cross section view. So, that you can understand how is the dispersion and how are we going to machine.

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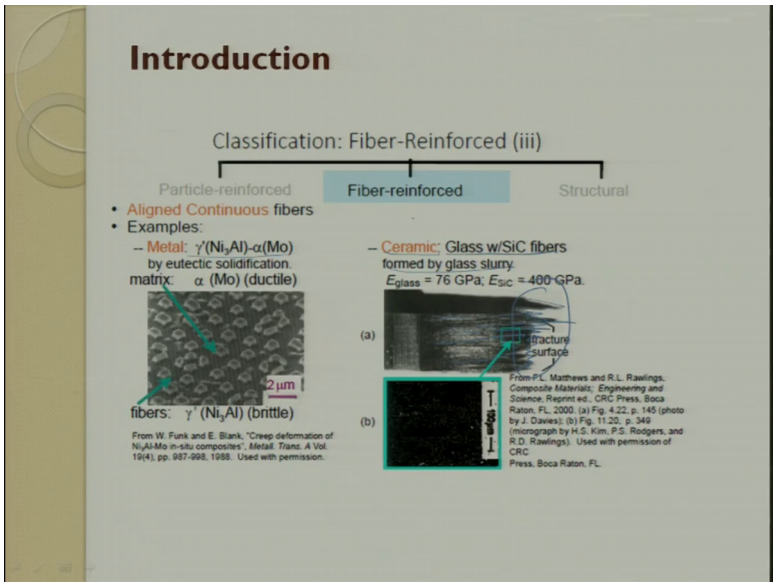

If you look at Fibre-Reinforcement so here you can see aligned continuous fibre. So, you see a metal here you see in matrix metal are Ni 3 Al Nickel Aluminide which is a alpha molybdenum. So, by eutectotic solidification it is made. So, here is a matrix and here are the 5 these are the fibres right these fibres are nothing, but aluminide nickel aluminide which is brittle. So, when you look at the glass fibre reinforced composite.

So, these are the glass fibres which are getting cut or the other way around you can have ceramic glass fibre tungsten which is there in A S I C fibre. So, formed by a glass salary so you can see when you try to machine, this is what you get the fractured surface. So, if you remember in the or you will see in the next lecture we will be discussing about repairing of composites. So, here you will how to repair the composite. So, there you will see little bit more how to handle such finished surfaces this is a example for fibre reinforcement.

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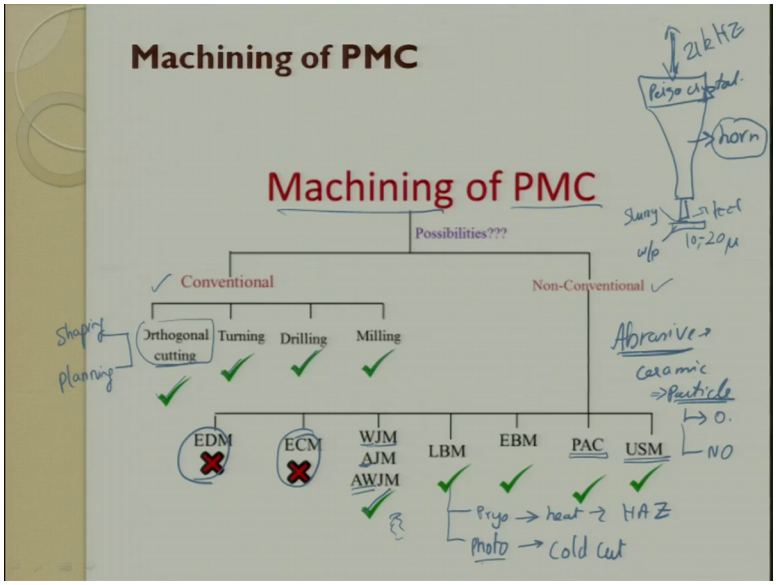

And the last one is for structural you can have laminate with varying orientations which we have discussed in length and the other way around a sandwich composites. Sandwich composites are lighter in weight they are they give lot of stiffness. So, you have a face sheet on the top, you have a core, which is of a lighter material, which gives in thickness and between the skin and the core you might have an adhesion layer or this to gets stitched of it is own by some adhesion epoxy whatever you adhesion resin whatever you use.

So, this is called as a fabricated sandwich composites these are structural composites which are used. So, these are the different types so we have seen what is particulate reinforcement what is fibre reinforcement and structural reinforcement.

When you talk about machining of polymeric matrix composite as I told you earlier Conventional Non-conventional, in this what are all the process which are available with

us which we can do machining. So, one is cutting orthogonal cutting basically orthogonal cutting means it is for Shaping and Planning. So, shaping is used for smaller workpieces, planning is used for planning is a is an operation we do it on a planning machine it is called as a planar. So, this is used for a very large bed or very long lengthy workpieces we always go for planning operation here we use a single point cutting tool and it is called as orthogonal cutting.

The next one is turning for cylindrical shafts or a cylindrical workpiece where you want to maintain axis symmetry we always go for turning operation and then we do drilling for generating hole and then we do milling operation for generating pockets. This is also for generating flat surface or inclined surface you can do depending upon the relative motion between the tool and the workpiece. So, these are the operations generally done what happened to grinding. So, grinding already it produces a very small chip and the material removal rate is very low, grinding is predominantly an operation which is used for finishing. So, here the polymer matrix composite both surfaces top and bottom you can always try to in the process itself you can integrate and bring in the smoothness. So, these are the very commonly used processes which are used for machining of polymer matrix composite.

When I talk about non contact type see what happens is polymer is a non conducting material. So, predominantly EDM process and ECM process cannot be used because the process needs a closure of the circuit. So, this will not happen in polymer matrix composite. So, these 2 processes are not thought of; however, in the recent research people have tried to give a coating on top of this polymer matrix composite and do EDM process as well as ECM process, but these processes are demonstrated, but it has not gone to the industry level the most commonly used processes are jet machining process. So, in jet machining process what we use is we use a jet, where this jet is of a very high pressure and this pressure is passed through a nozzle and then exactly focused at the workpiece. This nozzle is moved relative to the work piece and generates a geometry because of the high pressure this is used for cutting the workpiece.

So, the jet can be made out of water, the jet can be made out of abrasive the abrasives are predominantly ceramic and these are nothing, but these are particulates there are 2 type of there are 2 types of classification one is oxide ceramic and non oxide ceramics. So, here what we do is these are very small particles of from one micron to 10 microns you

can have and it is used. So, the abrasives are small particles these particles are pressurized and their mixed with a career gas. So, that they get the pressurized air exiting the nozzle while cutting and if you want to have an hybrid of air and water put together. So, those processes are called as abrasive water jet machining process.

The next process is laser beam LBM. So, in LBM process here the photons are used this photons are focused by a lens on top of the workpiece. So, the laser beam process has 2 2 mechanisms one is called as pyrolytic process the other one is called as photolytic process In pyrolytic process basically the photon when it hits the workpiece it gets the converted into a heat energy it melts and evaporates. The same with photolytic what happened in tries to siser or tries to break the bond and here it does not convert into heat it the polymer is directly converted into a gas; that means, to say something like a sublimation process goes on and the bonds are broken and you try to get a cut which is made. So, this is always called as a cold cut as compared to that this heating.

So, heating leads to a something called as heat affected zone. So, next one is electron beam machining; electron beam machining is predominantly used for very small holes to be made very small high aspect ratio. So, holes to be made, but here also it has a problem of closing of the circuit. So, this is a challenge the next one is a plasma assisted cutting; plasma assisted cutting is there are 2 types of plasma one plasma one is called as the plasma where in which the workpiece is also involved in closing the circuit, the other plasma is within the nozzle itself they have closed the circuits. So, those plasmas can be used for machining polymer matrix composite; however, it has a very high heat. So, we try to avoid using plasma arc welding.

So, in ultrasonic machining there is a Piezocrystal, this piezocrystal is attached to a tool. So, between the piezocrystal and the tool we have a horn the shape and the length of the horn place a predominant role to transfer the vibration what comes out of piezocrystal to the tool. So, the this tool vibrates vibrates at 21 kilo hertz 21 kilo hertz it is vibrates. So, that the tool also vibrates at the same, but the amplitude is 10 to 20 microns that is a maximum 10 between 10 to or between 1 to 20 microns. So, this is used for creating high aspect ratio holes and since and between the tool and the workpiece we pass abrasive slurry. So, a slurry is passed. So, this tries to hit the workpiece, this is a workpiece, this tries to hit the workpiece and remove the material which is there in the workpiece.

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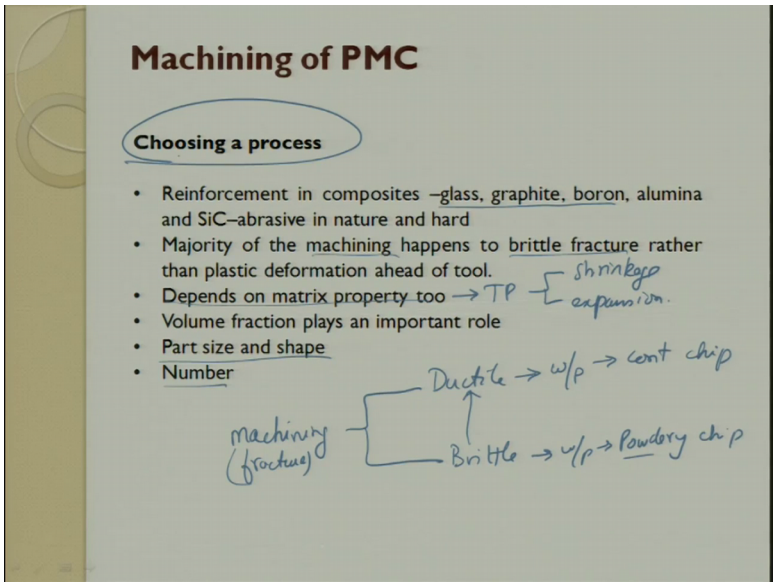

So, choosing a process the Reinforcement and composite can be glass, graphite, boron, alumina, and SLC. So, you have to look at the size shape of the reinforcement and decide your process. Majority of the machining happens by brittle fracture when you talk about machining there are 2 types of fractures machining fracture one is called as a Ductile fracture the other one is called as a Brittle fracture.

So, ductile fracture is predominantly the workpiece comes out as continuous chip in brittle workpiece we get a powdery chip. So, when you when you have a powdery chip it is very difficult for you to control the surface whatever you generate. So, in ductile fracture you can control and get the shape and the roughness whatever you want predominantly when you do machining people always try to convert from brittle fracture to ductile fracture, but where in composites what happens since we have a reinforcement and that is also ceramic you always have a brittle fracture which is coming out. So, this makes the process random in nature. So, it is very hard for you to control the surface finish on the workpieces.

Then depending upon the matrix property also for example, thermoplastic when you try to drill a thermoplastic that will be a lot of temperature as I told the workpiece has to take the temperature. So, when that when you drill a hole the workpiece takes the temperature and then either the whole expands or contracts when you drill a hole, then after a few hours this hole either tries to shrink or contract shrink or expand I repeat

depending on the matrix property. For example I take thermoplastic there can be a shrinkage or there can be an expansion, there can be an expansion of the polymer material. So, a drilled hole the geometry changes in due course of time the volume amount of volume fraction presence also plays a predominant role in generating the chip then part shape part size and the number all these things have to be thought of while choosing a process for machining of polymer metal matrix composite.

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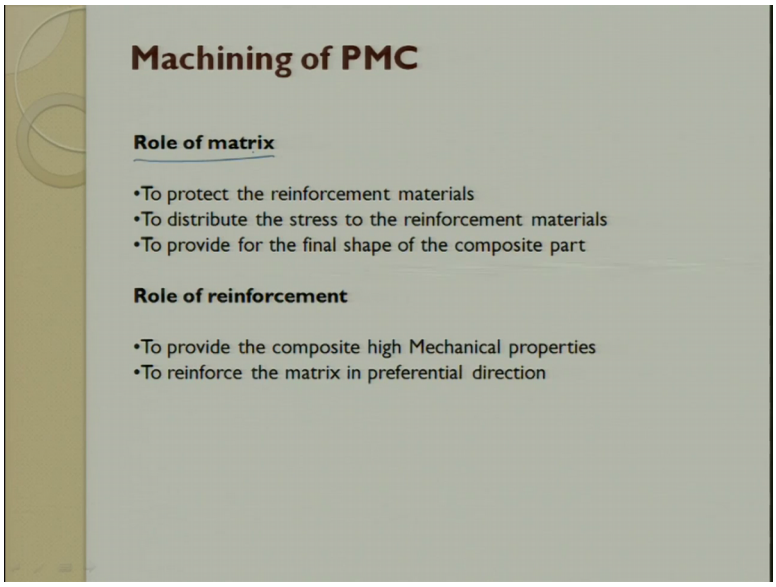

The role of the matrix which we have already seen so one is to reinforce the matrix material to distribute the load and to protect the reinforcement agent whatever it is to give a final shape, when you talk about reinforcement it tries to take the strength.

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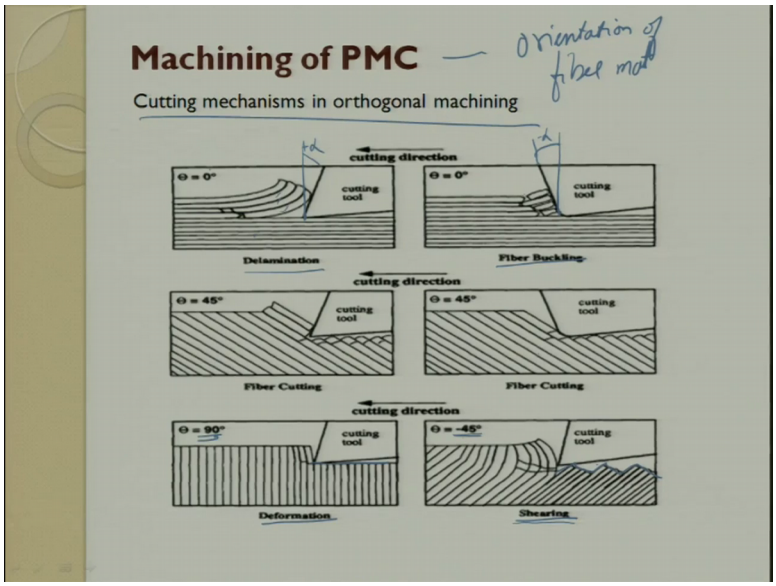

So, this is for orthogonal machining where and which I have put different plies of varying orientation. So, this orientation and you can see what happens to the fibre when you change the orientation and you cut the tool. So, this is the cutting direction. So, here orthogonal cutting shaping and planning are typical examples you see a sharp tool, you see a blend tool, this tool is having a positive rake angle, this tool is having a negative rake angle, this positive rake angle and if the orientation is 0 you can see the (Refer Time: 26:17) and the cutting tool moves is a cutting direction, when it moves you see that the layer by layer it is peeling off, you can control the depth and remove the amount of layers you want to do.

When you look at this when it is a negative rake angle you can see the fibre does not flow on top of the surface here the fibres are broken, and moment it is broken it becomes like a hard abrasive particles, when it moves on top of a cutting tool it is going to bring in lot of friction and wear. When I just change the orientation from 0 to 45 use the same tool you look at the fibre gets fractured and here when I talk about 45 with a negative rake angle you see that again these 2 phenomenas are fibre cutting fibre is cut. So, here it is fibre buckling so; that means, to say there is a fibre you try to compress the fibre and moment you compress it fractures and it buckles up.

This is de lamination with you see here when I try to make the orientation at 90 degrees and at minus 45 degrees you see there is a deformation happening; deformation means it

tries to bend and it tries to shear of and here you see there is a shearing phenomena happening. So, here you see the surface here you see the jump in the surface which is getting generated on the finished part. So, here when I do it with minus 45 degree orientation minus forty 5 degree I get a shearing mechanism. So, you look at it depending upon the orientation of the orientation of the fibre mat, you see different mechanisms come into existence and this is this is just for talking about fully start with forty 5 fully start with 0.

But generally what happens is we have a quasi isotropic. So, we would like to have varying orientation getting start. So, at every ply different mechanisms get into existence and this tries to produce lot of force fluctuation while machining this force fluctuation tries to directly affect the affect the response of the tool. So, that is why while machining composite material we always say please use toughened tool so. In fact, H S S High Speed Steel give you a better performance, but the only problem with high speed steel is it cannot with stand very high temperatures it softens and it gets owned out very fast. So, there has to be a compromise if you use a hard tool and a stiff tool again while machining of composites it is going to be a problem and here the machining nowadays machining happens at 100 metres per minute. So, at that speed force fluctuation the tool response becomes very poor.

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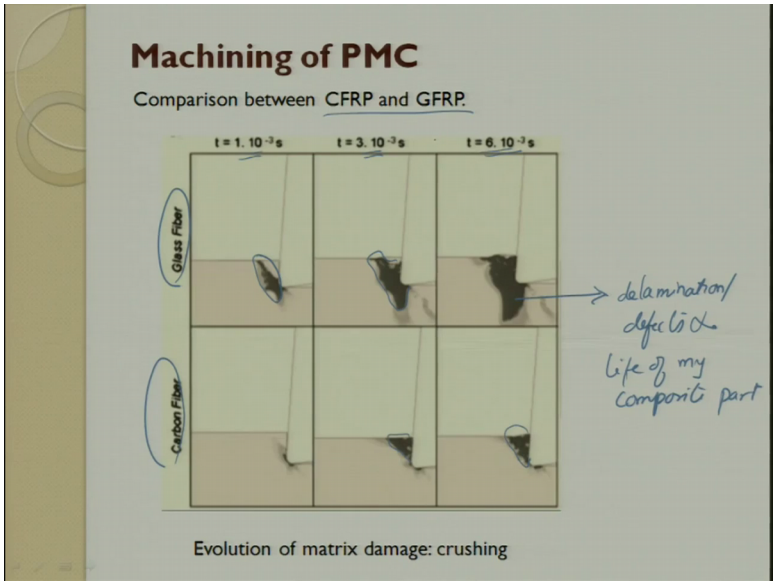

So, if you look at CFRP and GFRP this is a glass fibre and this is the carbon fibre you see that when it is cut when it is cut at a different time scale has been given. So, when it is cut you see the amount of damage it is getting created while machining. So, what are these damages these damages are going to lead me to delamination; delamination and other defects. So, this is directly proportional to the life of my composite part, this is going to be directly proportional to the life of my composite part.

So, I would like to do as small damages possible and here in carbon fibre the damage is less because carbon is having better stiffness or it can take little bit of fluctuation in the force, carbon can take as compared to that of your glass fibre. So, you can see here the this is you can see crushing happening a just before the tool at varying time scales. So, at varying speeds when I do so you see that the chip flows in different directions right. So, this you can see again I have compared with glass fibre and carbon fibre.

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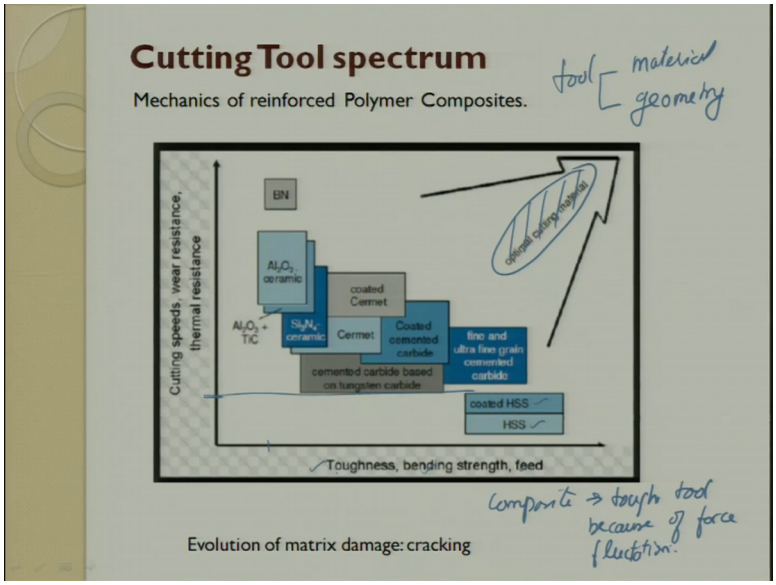

So, here is the spectrum of tools which are available in cutting. So, here if you have to choose a proper tool for getting better performance as I told you this property in x axis you have toughness bending strength and then feed. So, here if you see HSS and coated HSS gives you a wonderful performance, but the cutting speed wear resistance and thermal resistance are extremely poor for this HSS, we would like to have higher toughness, we would like to have higher wear resistance and thermal resistance, we would like to go for higher cutting speeds. So, what we wants is we want a material here

to machine composites, but unfortunately today we do not have any material tool material which can do very good composite cutting though in a tool there are 2 things one is tool material tool we have tool material as well as tool geometry; geometry can be generated, but a tool material is a challenge.

So, we would like to have materials in this zone which is not available today if you see tungsten carbide cobalt, it has a slightly lesser toughness, but the speeds can go high if you keep going you see alumina reinforced this is a ceramic composite. Alumina ceramic ceramic composite alumina reinforced with TIC you have. So, this is having a very it can go to high speeds, but the toughness goes very high boron nitrate gives a very high wear resistance, it can help you in going to very high cutting speeds thermal resistance, but the toughness is a is very low, but while machining composites we need to have a tough tool or tough tool because of force fluctuation what happens you can see different tools how are they are responding with time.

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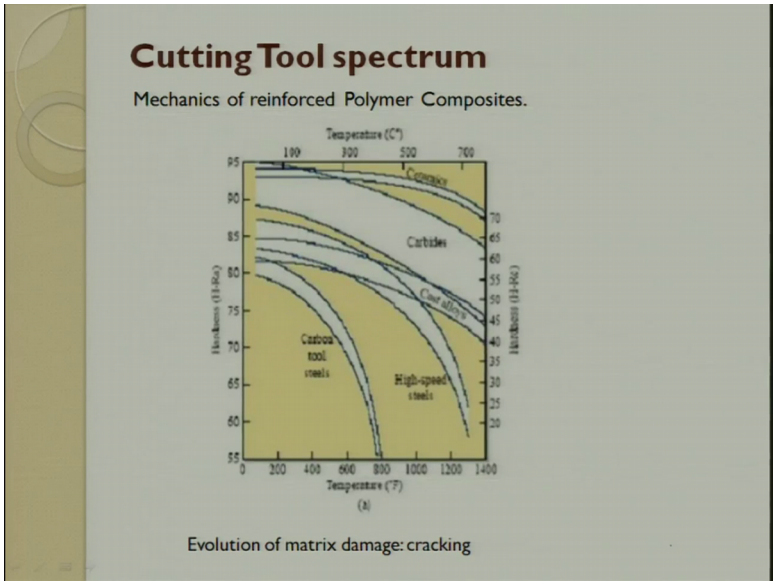

So, you can see here the hardness. So, the hardness property falls down drastically. So, you try to take this is a carbon tool steel. So, from the eighty HRC it just fall down to 55 HRC by going to 800 degree fahrenheit. So, when you take carbides from 95 it goes to somewhere around 70. So, here is a response where and which we have drawn with respect to hardness and temperature. So, you can see that as and when the temperature goes high of the surrounding there is a steep fall in the hardness property.

For example for a carbon tool steel from 80 HRC it goes down to 55 HRC by reaching a temperature of 800 degree Fahrenheit, when you take a carbide from 95 it goes up to somewhere close to 75 by at 1400 degree Celsius fahrenheit. So, it is very clear as and when the temperature goes high the hardness property goes down hardness goes down wear resistance goes down. So, this is very important. So, now, you can understand there is a complexity while machining and on top of it the tool geometry whatever is there also softens and changes distorts. So, moment both these action come into existence we will never be able to get a proper cut.

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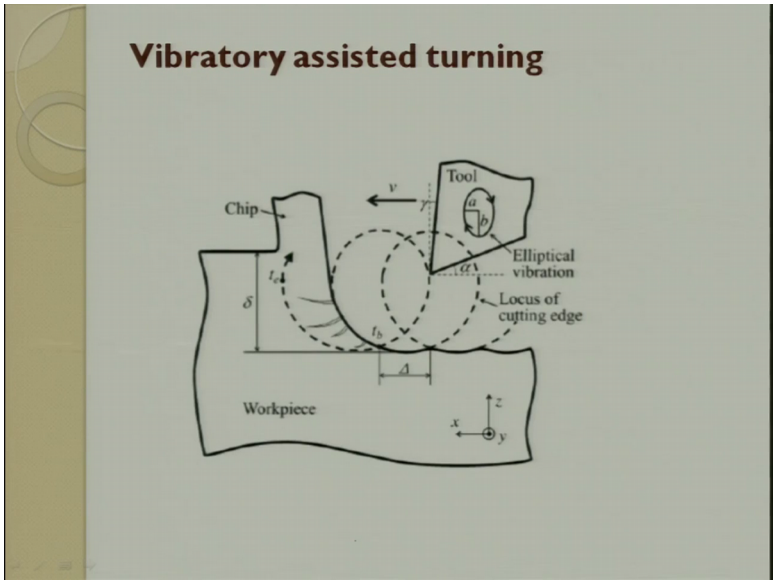

So, what people have done is people have thought of various ways. So, one way of doing it is in turning itself rather than having a continuous contact of tool and the workpiece what they said is why do not we try to have vibratory assisted turning. So, vibrate assisted turning vibratory assisted drilling is all used. So, what they do is they try to give a small vibration to the workpiece so the vibration can be along the z direction or can be along the xy plane.

So, when you do that they are trying to remove the complete contact of the polymer matrix composite with the tool and give a small elliptical motion. So, that they try to reduce the damage and also tries to make sure that the heat gets distributed from the tool tip slightly. So, this is going to enhance the machining performance, and once it is

enhanced the amount of damage to the workpiece is reduced because now the tool geometry is retained for a longer time.

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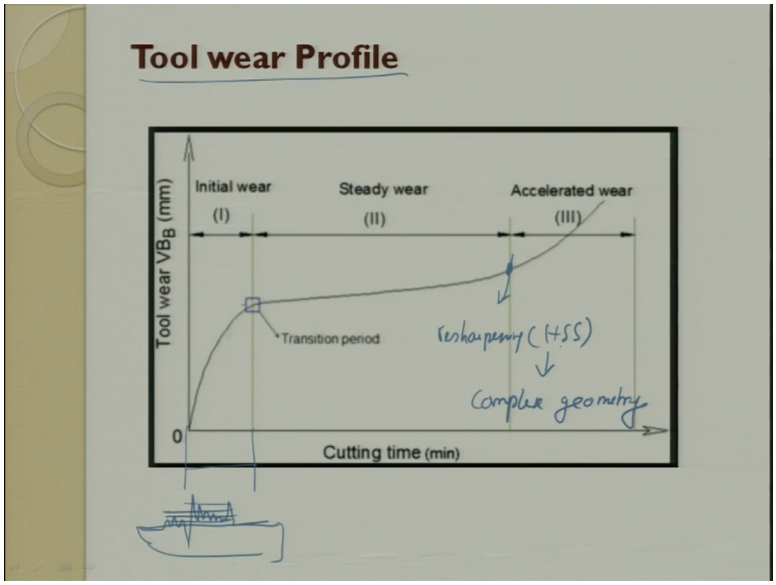

So, when you talk about a wear profile you will always see this is the response of the wear profile. So, it is called as initial wear then you will have a steady state wear, then you will have an accelerated wear. So, generally what happens when you try to use HSS tool we will try to re sharpened at this place re sharpening happens at this place. So, we always would like to work in the comfort zone of this. So, this initial wear happens in a very small time. So, basically what happens on the tool profile there will be some asperities which are very which are very thin and light, but these asperities will try to die of very soon during the initial wap and such that a large surface area comes in contact with the chip. So, this is a steady state wear and this is an accelerate wear.

So, this re sharpening is possible only for HSS tool why am I talking predominantly if you have a complex geometry we always used only HSS tool if it is going to be a straight simple like a hole a simple hole a cylindrical part a square box a pocket if you want to make. So, then we go for a simple geometry if you want to do a slightly complex job. So, then we always go for HSS because it gives you a freedom of grinding re grinding re sharpening. So, that you get to retain the old profile.

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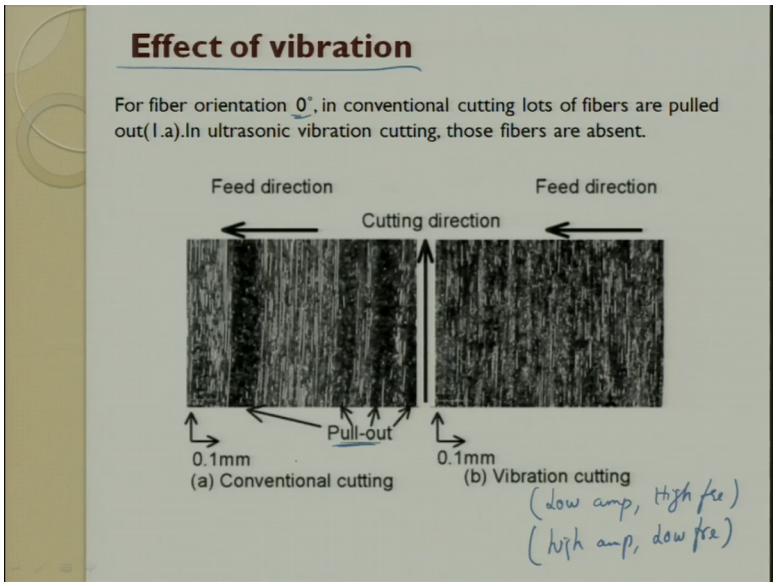

So, when we do with respect to vibration what happens is you can see the orientation in 0 direction and you can see orientation. So, this is the orientation with 0 degree and this is this is conventional cutting this is vibratory assisted cutting. So, the vibration can also be low amplitude vibration low amplitude high frequency or it can be high amplitude low frequency, you can use any one of the vibration and try to get it. So, when you try to do without vibration you and that to in 0 orientation, I am talking about only 0 orientation you can see there are lot of fibre pullouts coming in vibration there is not visually scene fibre pull out. So, fibre pullout means the fibre is getting pulled out from it is original position and then it is going to deturate the service condition of the part. So, here in vibration assistant it is not seen.

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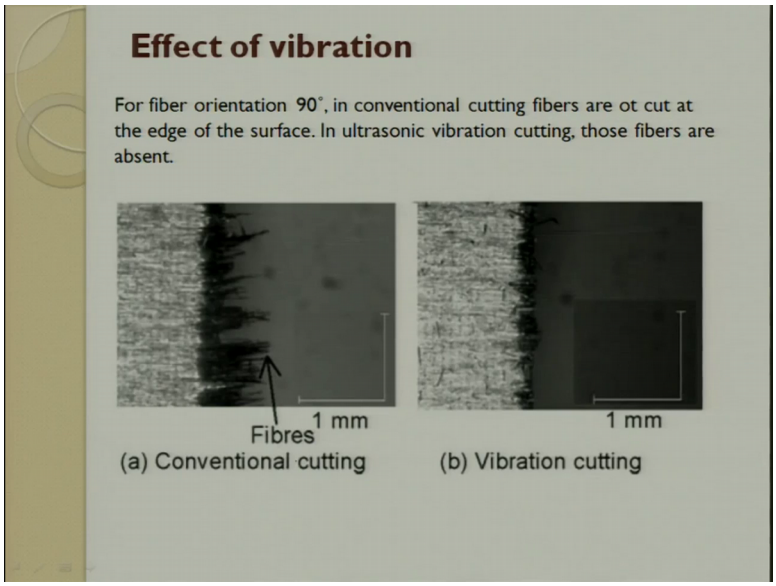

So, when you see that at 90 degrees you see there are lot of fibres which are getting pulled out and there is this fibre which is getting pulled out are not also cut properly, but whereas, when you see a vibratory assisted there is a proper cutting and the fibre pullout is not there see if there is a fibre pull out after doing an operation it is very difficult for you to trim the fibre and get the required output.

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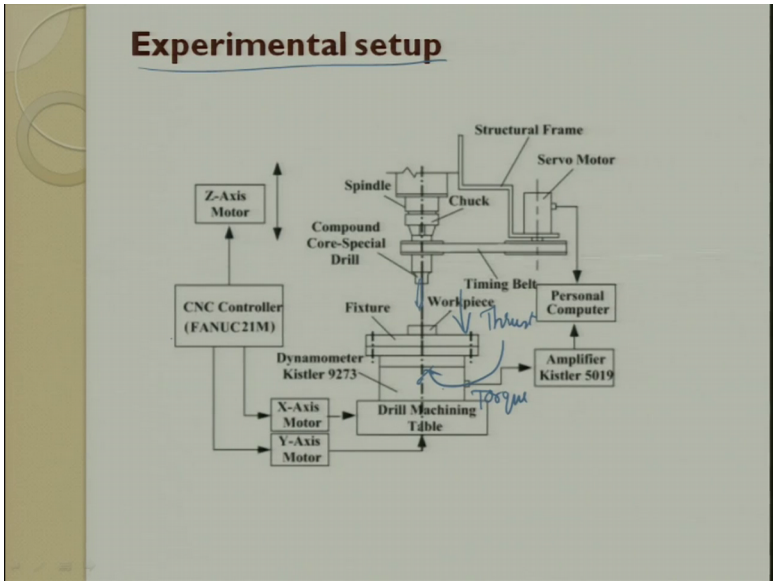

So, if you see a typical setup of a force measuring setup. So, we will have this if you look at a simple experimental setup for drilling alone. So, we will have a spindle and the

drill is mounted here we will have a workpiece and we have a dynamometer. In this dynamometer in drilling we will always measure a thrust force and a torque force, we will measure a torque force resistance to rotation is torque and the download moment is a trust. So, we always used to measure these 2 and then try to see what is the response while machining.

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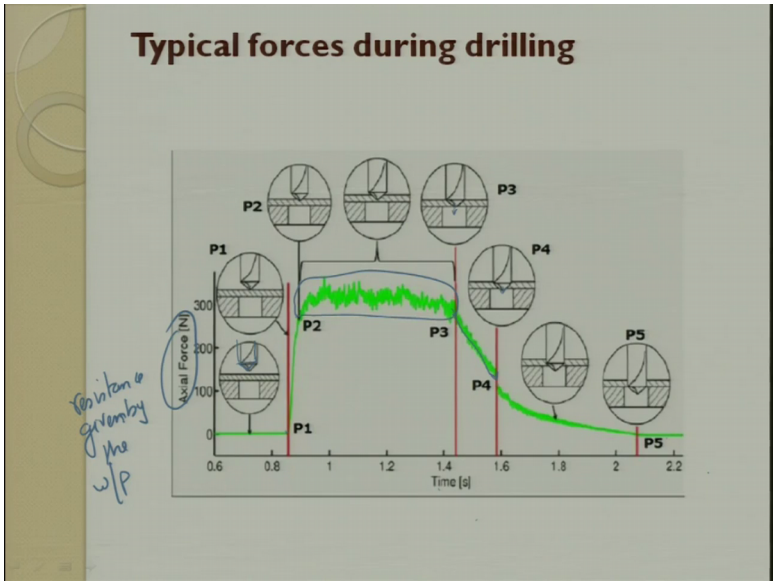

If you look at a typical drill you can see as and when the drill has not entered if you see a drill it is interesting you will have a triangular portion and then you will have a cylindrical portion. So, this triangle portion is called as a conical area this conical before the conical area touches the workpiece you see there is no change in the axial force axial force is a download force, moment it touches you can see that the force increases from 0 it goes up to 300 the magnitude of the force depends on the resistance given by the workpiece. For example, thermoplastic will have a lawyer magnitude metals will have a higher magnitude thermosets will have in between these 2. So, when the moment it touches the load increases to P 2 or from here touches this is what it is to form P1 it goes to P 2. So, you can see here this is a time.

So; that means, to say that drill is rotating and the drill is moving down. So, you have given a feed rate. So, it touches. So, moment it goes to P 2 the conical portion comes in contact with the workpiece you see here there is a force increase and moment it is there there is a fluctuation which is coming, this fluctuation is because of the presence of a

fibre there and very orientation of the fibre tries to dictate this fluctuation. Moment at tip comes in contact the first thigh what happens is it tries to extrude the material extrude the polymer material into it. So, if you see here moment the entire conical portion has entered into inside till that time the force increases and then comes down and it maintains at P 3 the conical is completely inside the workpiece now after P 3 the conical portion comes out.

So, when the conical portion comes out there is a fall in the trust force you can see there as and when it is exiting that the resistance goes down the stiffness offered by the workpiece to the tool goes down. So, you can see the force declination and then when it goes to 5 you see that completely that release out, you can see the thrust force coming up. So, with this you can try to see what happens to the thrust force at several instances before entry at the time of entry during drilling and then exit starts and exit ends. So, this is how the force profile looks like. So, this is this is another example which I have put.

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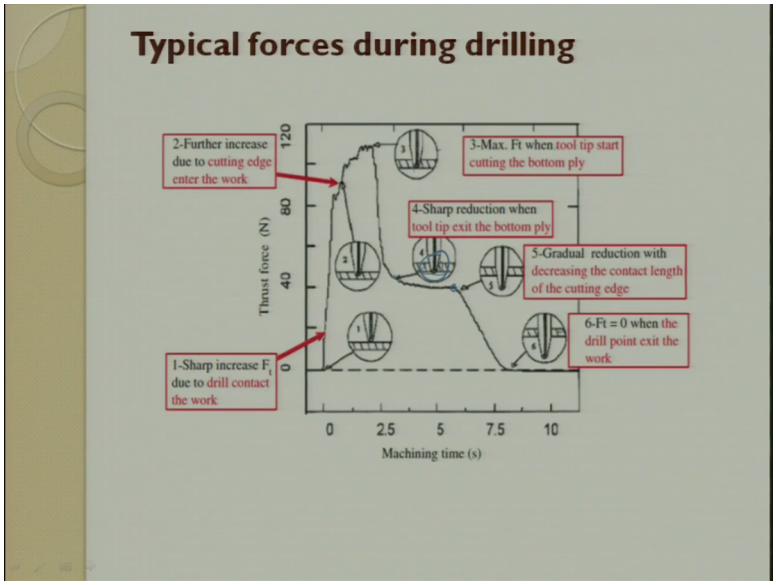

So, you can see the sharp increase is due to drill coming in contact with the workpiece, then further increase due to cutting edge entering into the workpiece, the third portion is maximum force when the tool tip starts cutting the bottom line this will be the maximum force, after that what happens there is a (Refer Time: 42:50) sharp reduction then when the tool tip exceeds the bottom ply and then you will have a gradual reduction with the decrease the contact length of the cutting edge will happen here and then the drill gets

exited out then it goes out. So, these are the 6 steps which happens as and when the drill enters and goes out this force diagram is very very important if you do not understand this force diagram what happens during the process.

So, here during the process here there will be lot of delamination phenomena happening, see what happens here there is lot of amount of workpiece material which gives resistance to the to the work tool cutting. As and when it goes to the last ply the resistance goes down the stiffness which is offered by the workpiece to the tool goes down. So, at this point with the same force what happens it tries to eject out. So, when it ejects out it is going to create a huge delamination the we are supposed to understand this and try to play with the forces such that that delamination does not happen.

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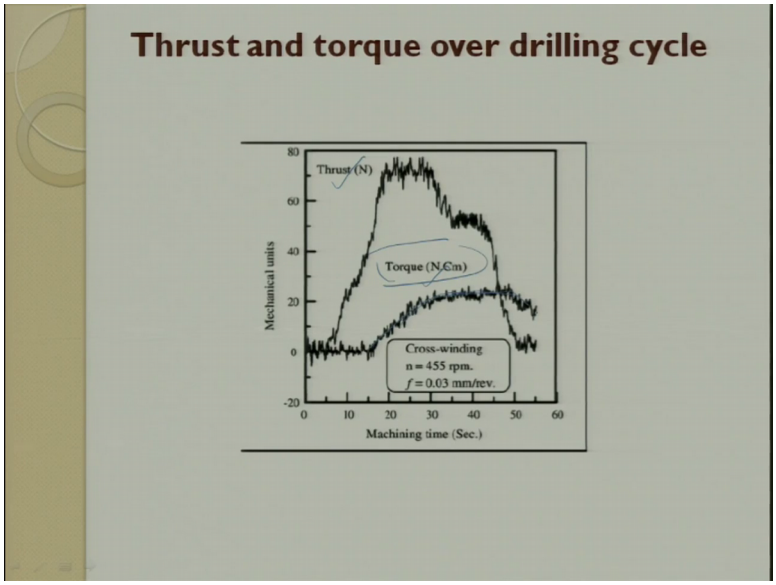

So, thrust force are always higher than the torque force. So, you can see the response of the torque force which keeps going on and on and on and then fall down why because the torque force keeps on increasing and then going further and further because this is a rotation motion which is in the tool when it rotates it comes in contact with the whole. So, and then it this force keeps increasing at once it exceeds out also. So, if you go back and see here even during the exit out the exit there is a resistance the tool is given a resistance by the workpiece. So, the force will keep continuing at some level the torque force is always lesser than the thrust force.

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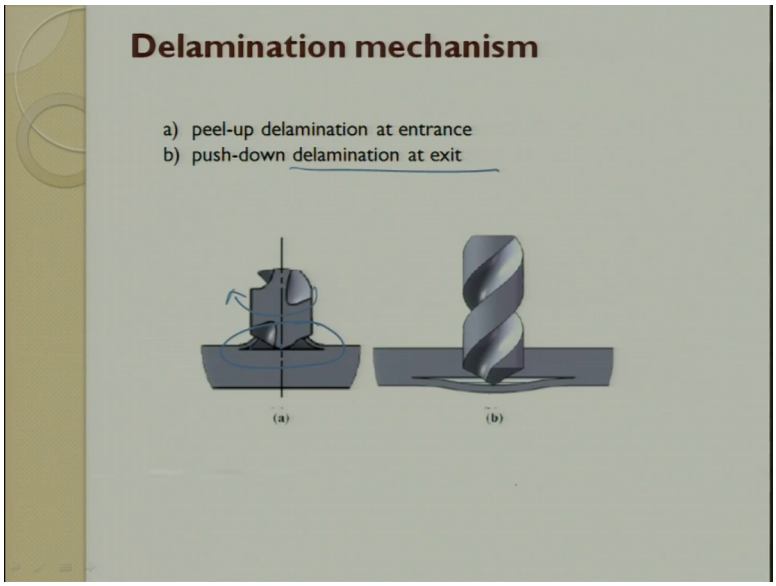

In the initial stages of drilling you will have a you will have a phenomenon called as peel up phenomena. So, this the tip enters inside and when this rotation happens to this will try to indent and try to pull, moment it tries to pull it tries to do a peeling up operation at the entry and when the when it comes to the last ply; that means, to say bottom almost close to the bottom exit it all the stiffness offered is less. So, there is going to be a huge amount of fibre or we will call it as push-down delamination at the exit. So, peel-up of delamination and push-down delamination peel-up delamination is not so prominent because after this peel up also since it is going to drill that surface. So, this is getting compensated, but push-down phenomena the damage is going to be very high. So, this delamination to a large extent has to be control.

So, you remember I told you several not destructive techniques we use those non destructive techniques and try to quantify and see what is the amount of damage it has created? Then accordingly we try to choose the proper process parameters.

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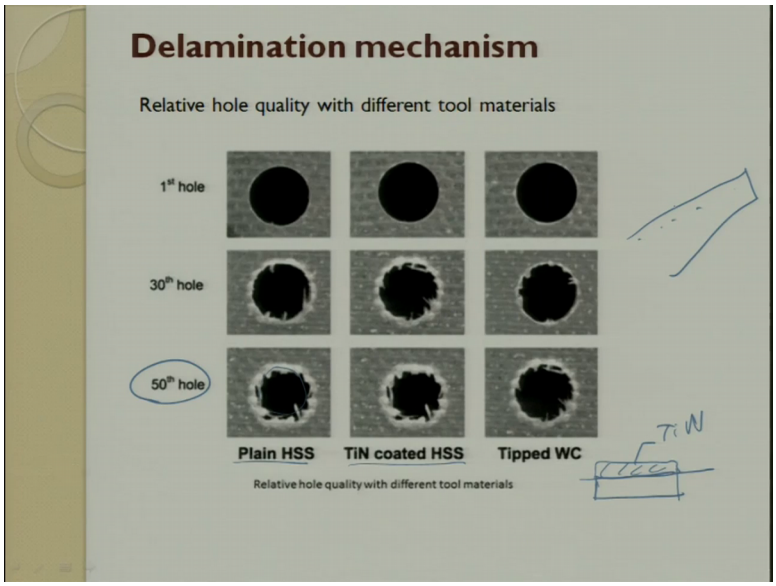

If you look at it the first hole thirtieth hole and 50th hole if you look at plain HSS because of the tool geometry getting distorted you see the fibre is not getting cut, but the fibre is pulled out of the matrix and it is left there. When you look at titanium coated; that means, to say I wanted to enhance the temperature wear resistance. So, I do a coating on top of this HSS tool and you see there is a slight enhancement, but it is not. So, in the first one it is second one.

So, here if you see the damage it looks slightly higher or it is almost maintain the same. So, here you should understand when the TIN coating is given, the coating thickness place a very important role if it is done by ACVD rule the coating thickness is high. So, then there is a possibility of coating and the interface between the tool and the coating this is the coating, if the thickness is high then there is a Delamination at the interface happening and then this TIN peels off.

So, sometimes coated HSS performs poor on longer run as compared to that of the plane. So, if you look at tungsten carbide the tool geometry is not damaged in a big way. So, the responses are good up to 50 holes. So, that is why when you see in aero industry when they have a large wing where they do several holes, they just keep changing the drills after drilling 5 holes or 10 holes. They do not check all these things they have established an experimental model. So, for every 5 holes or 6 holes they keep changing the drill and then they keep going.

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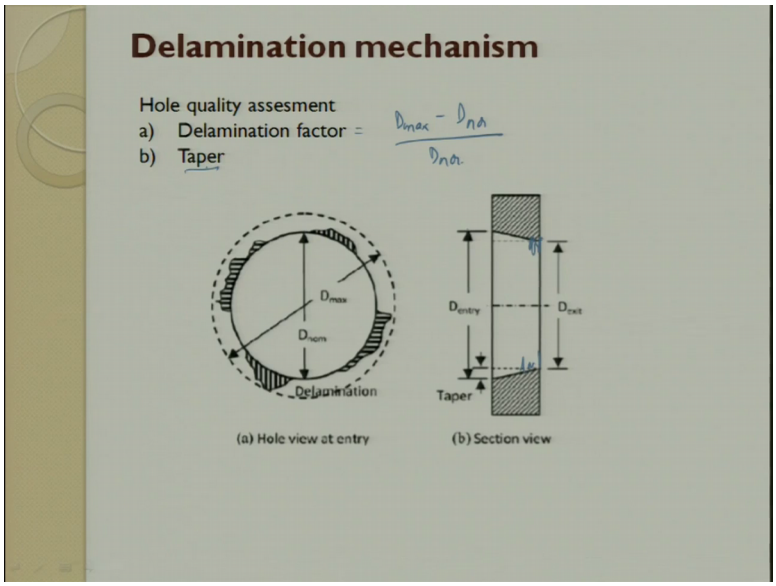

When you look at the damage which is created because of drilling so you can see that this is the diameter nominal I wanted and this is the diameter which the maximum damage diameter. So, this can be expressed in delamination factor which is nothing, but D max minus D nom by D nom. So, you will always have it in terms of ratio and this ratio we will try to maintain it as low as possible and if you see the delamination it need not be uniform all across it happens at several purchase.

A next one is the taper what we have. So, you can see that when we entry this is the entry part and this is the exit part and here on top of it you will also have the fibres which are projecting. So, this is a taper. So, these 2 qualities have to be maintained when you try to drill a polymer matrix composite.

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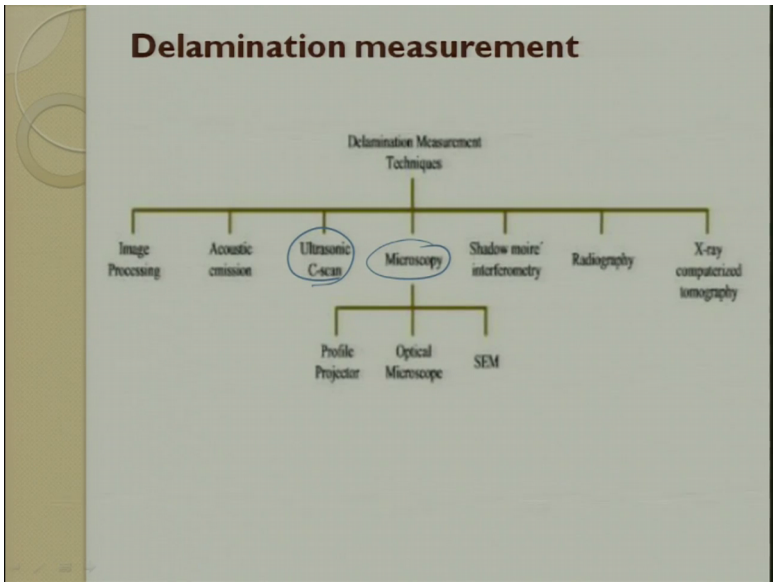

So, that the several delamination measuring techniques we have seen in the non destructive testing lecture series. So, we predominantly use microscopic and ultrasonic scanner to find out the defect delamination and the response.

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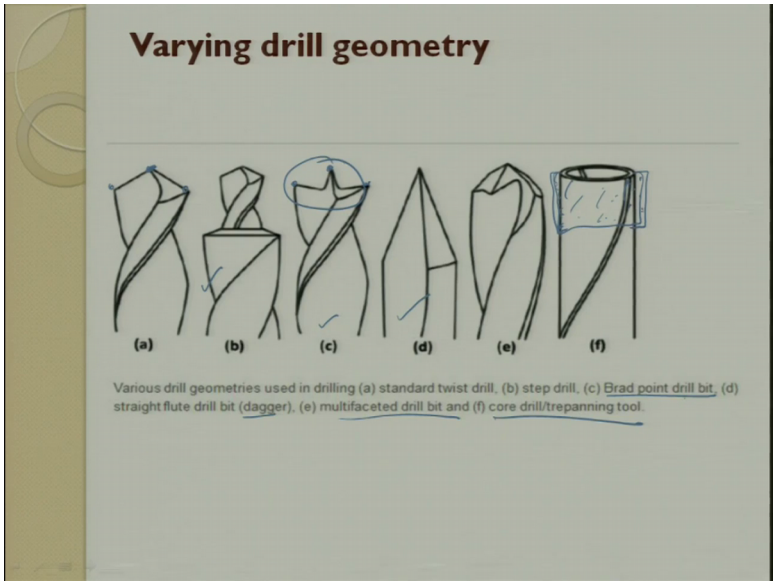

So, now you see here there are various drill geometry which have come into existence. So, these drill geometries make sure that the thrust force is reduced to a large extent, if you reduce the trust force the pushdown delamination can be reduced in a large way.

So, this is something like a tripod. So, we have one 2 and the centre position. So, the chisil this is the chisil head is now converted into a point and these 2 edges are converted into other 2 points. So, here the thrust force reduces in a large way. So, this is called as braded point drill bit. So, in braded point drill bit the geometry is changed and the thrust force is reduced, but these are this is a standard drill bit, so this is a stepped drill bit.

So, then you have a braid then you have a straight flute, which is there or it is also called as dragger then we have multifaceted drill bit. So, instead of 2 face they are having multifaceted. So, drill bits are available you also have cylindrical drill bits, where and which it is coated with diamond abrasives. This operation is called as trepanning operation you have a core a cylinder and then a cylinder in the cutting portion is here top we try to disperse it with diamond abrasive particles. So, here this because the chip is not continuous you get a powdery chip this geometry is also accepted for drilling of holes.

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So, this is a figure whatever I was talking to you about. So, people have also tried to this is Diamond abrasives coated on on Core drill. So, you can on a core drill. So, core you can see a core twist drill you can see a core saw drill, these are core saw drill, then you can have a candle stick drill, then you can step cone drill. So, these are all different geometries today which people are using to reduce the delamination in a big way.

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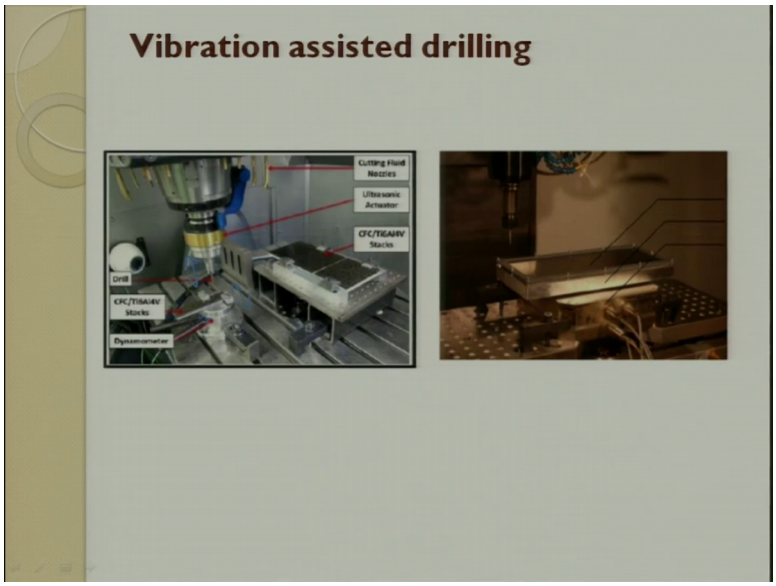

So, as I was discussing in turning people have also started using vibratory assisted either the workpiece is vibrated or the tool is vibrated, again in ultrasonic frequency or a frequency which is lower than that.

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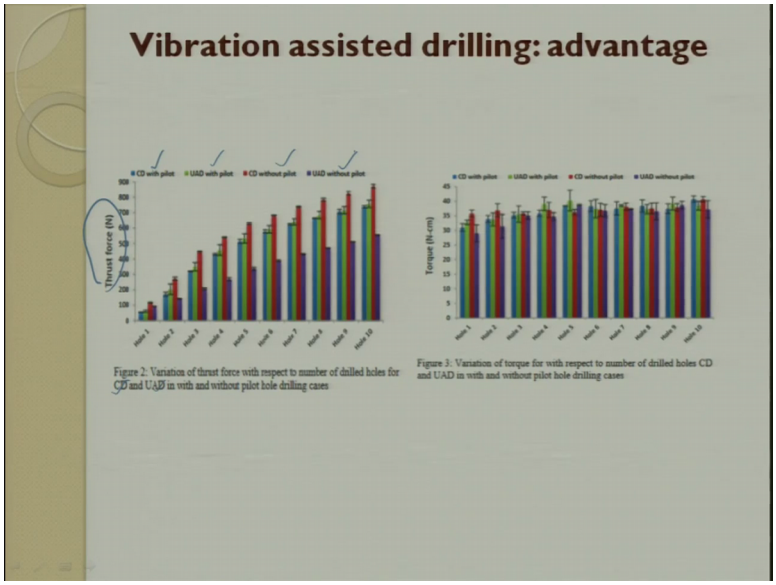

So, you can see the enhancement in performance of see the thrust force this is for vibratory assisted and the this is for non vibratory assisted. So, you can see the variation in the thrust force with respect to number of holes drill for CDUID these are a vibratory assisted drill and this is a conventional drill they have done and you see the response

whatever it is. So, this is CD with pilot, vibratory assisted with pilot, so CD without pilot and UID vibrator assisted without pilot. So, you can see the difference in response how is it

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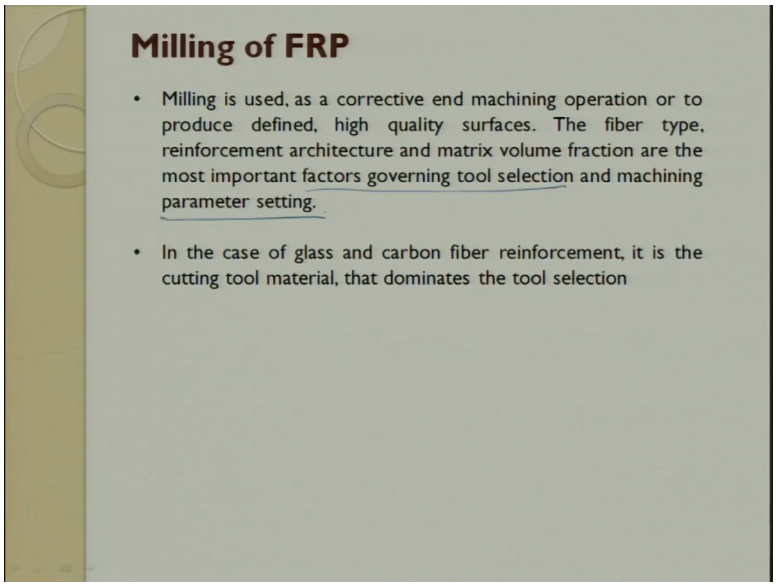

So, Milling of a FRP composite which we are talking about milling is generally used as corrective end machining operation to produce define or a very high quality surface. The fibre type, reinforcement architecture and the matrix volume fraction are the most important factors which govern the tool selection and the machining parameter selection. So, what I am trying to say here is if the volume fraction is 10 percent if the volume fraction is 100 for the same or eighty for the same thermoplastic or thermoset the process parameter and the tool geometry changes. If more the matrix the chip to a large extent can be continuous, if more the particulate or more the reinforcement it will be all powdery chip. So, in case of glass and carbon fibre rein reinforcement it is a cutting tool material that dominates the tool selection.

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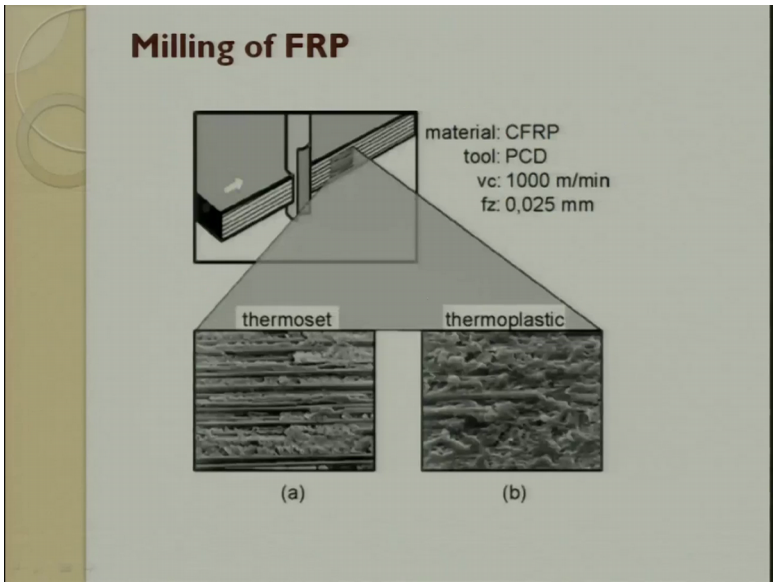

So, you look at it thermoset and thermoplastic thermoset the cut is clean because the matrix cannot expand or contract it is already set cured. So, you get a good cut of matrix and you see the fibres running along. So, in thermoplastic what happened it is there is the matrix get soften and it gets re solidified. So, you see there is a improper cut in the matrix. So, this is because of the recyclability property or if you see at the microstructure cross linking is hundred or very high here cross linking is very less here. So, because of that the after cutting is over the polymer tries to discharge and bring in a roughness. So, you see this figure this figure clearly states there is a difference in the signature after cutting thermoset and the thermoplast.

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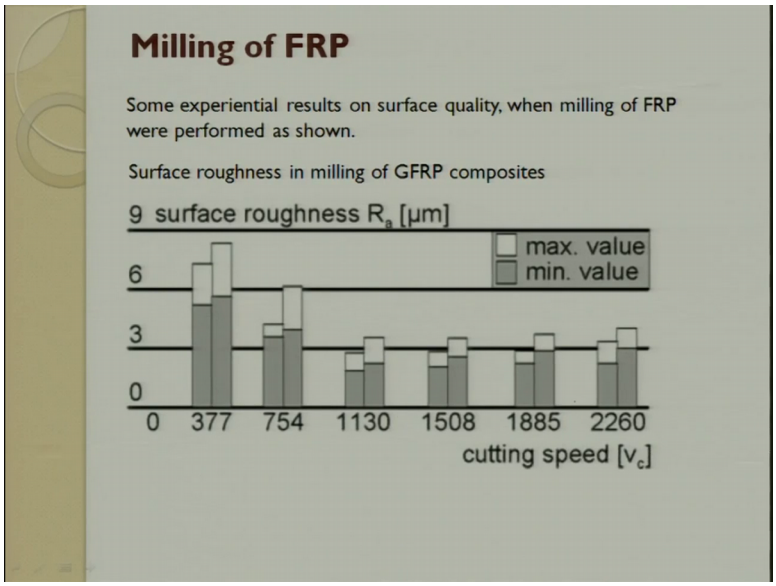

So, this leads to roughness. So, if you see here roughness variation between the 2 you can see these are the values for milling.

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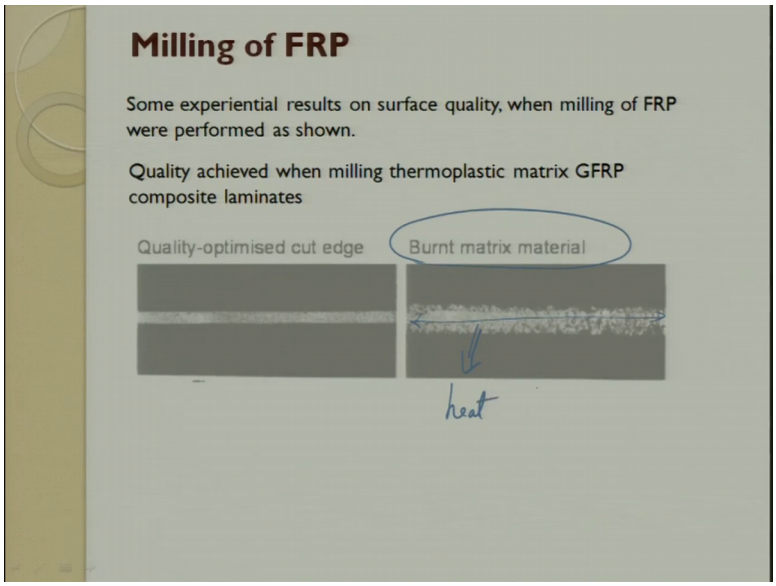

So, if you get a optimised cutting edge, if you want you can see this is the top view you can see a milling cutter is cut and then you can get a you can get a perfect channel made. If you try to use a burnt matrix material so what happens is there is a distortion which is happening along the running direction and the tool geometry is hit. So, some experiments results on surface quality when milling of FRP were performed as shown the quality

achievement milling a thermoplastic matrix composite you can see a perfect cut optimised and here you see a burnt matrix material because there is lot of heat which is getting generated.

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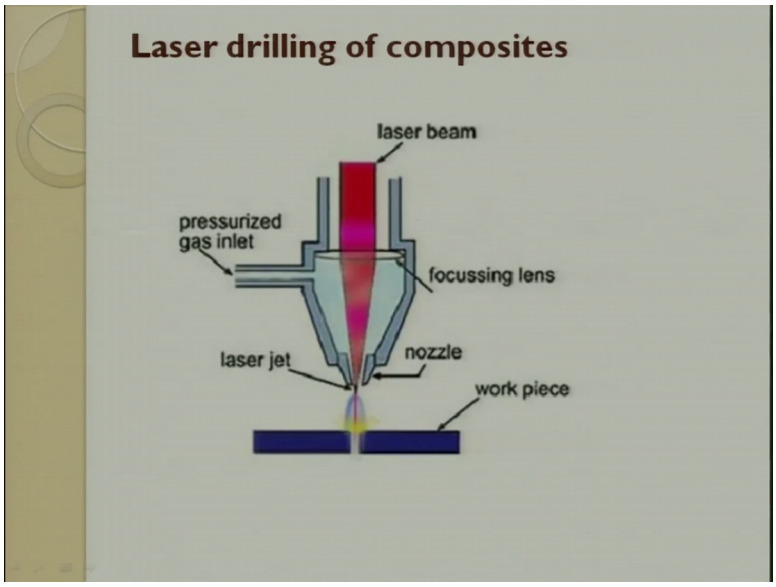

Going to non conventional the most popular one is glass fibre reinforce is laser drilling composite, in laser drilling composite laser beam photon lens, you reduce the diameter, there is a laser the laser jet comes and hits if you want you can also have a career media to gas to support and then try to make a jacket and then used for cutting.

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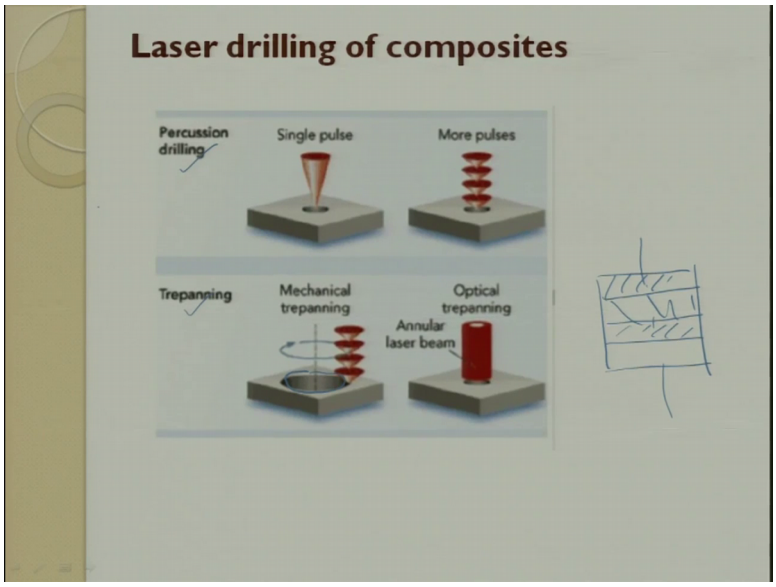

So, the laser drilling can be done like this you can do something called as a percussion drilling, you can also do a trepanning drilling trepanning drilling is you try to move around the around and generate a hole and then you do it step by step by step say for example, if you want to do a hole first you do up to here, then you do up to here, first this is the first layer, this is a second layer, this is a third layer, you can keep doing it and you move it in circles and get it done.

The other way around is optical trepanning also can be done and annular laser you can change the profile of the laser and annular portion can be thought of and it can be drilled. So, percussion so what you do is you put a single pulse you put more number of pulse, you burn, layer by layer spot you do not move the machine, you or the laser you just keep it and then keep hitting at the surface move the workpiece and get it done. So, both approaches are possible if it is a larger area we always use trepanning, if it is a small area smaller diameter drill we always do percussion drilling.

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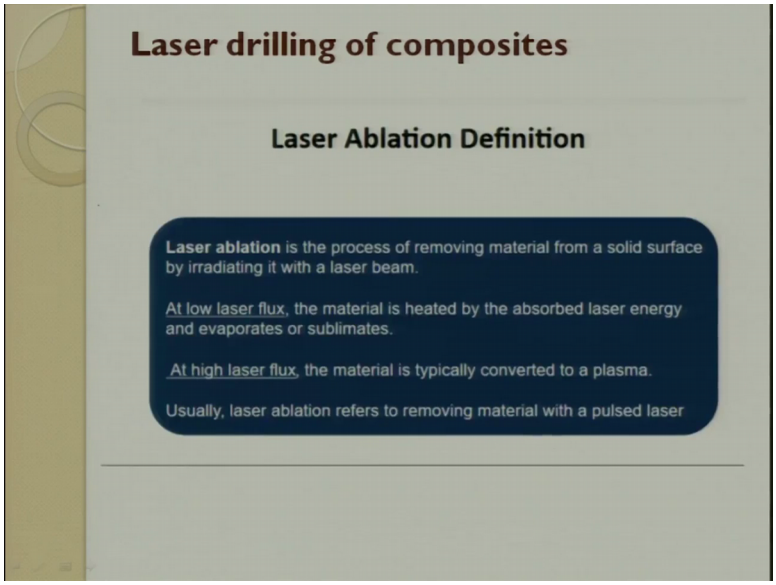

So, here in laser it is predominantly heat. So, it talks about the laser flux; laser flux is nothing, but joule per area. So, laser ablation is a process of removing material from a solid surface by irradiating with a laser beam, at low laser flux the material is heated by the absorb laser energy and evaporated or sublimated at higher laser flux the material is typically converted to a plasma, usually the laser ablation refers to removing of the

material with a pulsed see what happens when we try to remove the remove polymer material while using a laser this plasma is also getting formed.

The laser the machining of laser has a hue is a big science behind it. So, there is recoil pressure which is coming into there is a plasma which comes into. So, all those things are beyond the scope of this lecture. So, all we have to know is this is what I talked about photolytic and this is what I am talking about is a pyrolytic pyrolytic. So, pyrolytic means heat is applied for removal photolytic means heat is applied the heat there is no heat the laser has a wavelength this wavelength interacts with the bond and it is sisers the bond the polymer gets sublimated.

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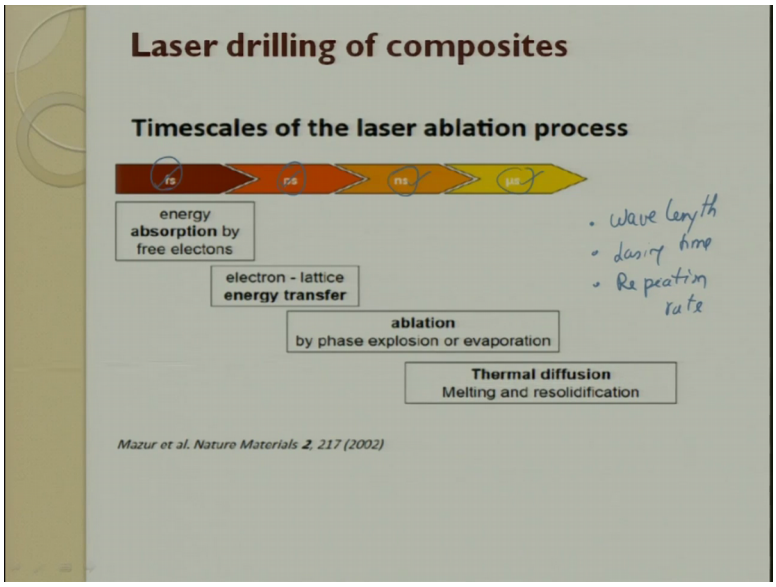

So, laser the number of pulse it can be femtosecond laser it can be a pico second laser nanosecond laser it can be a microsecond laser. So, when it is a pico second laser the energy absorption the absorption by free electrons happens, when it goes to the pico second laser the electron lattice energy transfer happens, then when it goes to nano it is ablation by face explosive or evaporation, when it goes to micro it is going to be a thermal diffusion it is more going to be a melt and re solidification. So, I have given you the mechanism. So, this is the pulse interaction time with the workpiece. So, you will have so what are the important things are wavelength of laser is very important, then you have time lazing time and then you also have a reputation rate, which talks about in kilo

hertz. So, all these things play a very important role in deciding the mechanism of material removal from that.

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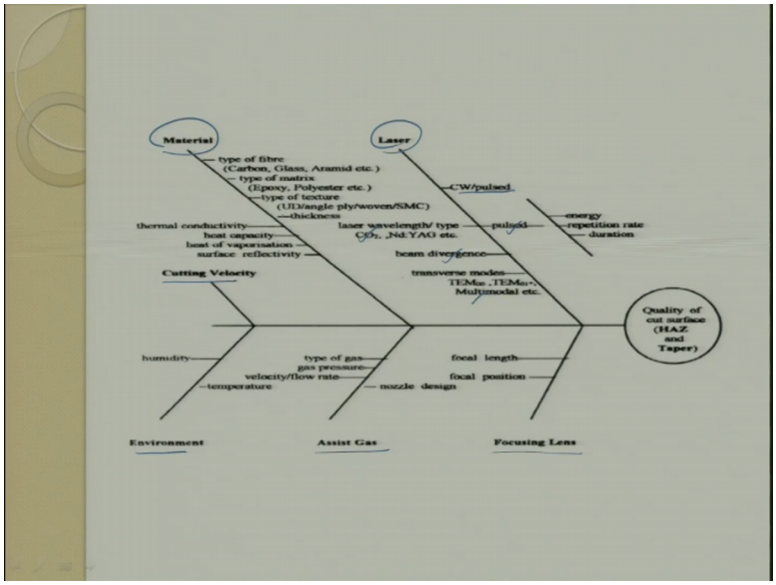

When you talk about laser, these are all the different process parameters which are involved in optimising the heat affected zone and the taper to get a good hole or to get a good slot done. So, cutting velocity is important environment is important we can use assistant gas then focusing lens plays a very important in focusing lens focal length and focal positions are very important then when you talk about laser, it talks about whether it is continuous laser pulse laser, what is the source beam divergence, what is the mode whether it is pulse, then wine pulsed what are all the reputation rates and other things.

So, all these things are different process parameters which are used to see which have to be seen before deciding the process and before making the choice of the laser. So, here you can see type of fibre it can be carbon glass are made matrix can be epoxy polyester, the texture can be unidirection angular oven or SMC the thickness also plays a very important role as far as material is concerned.

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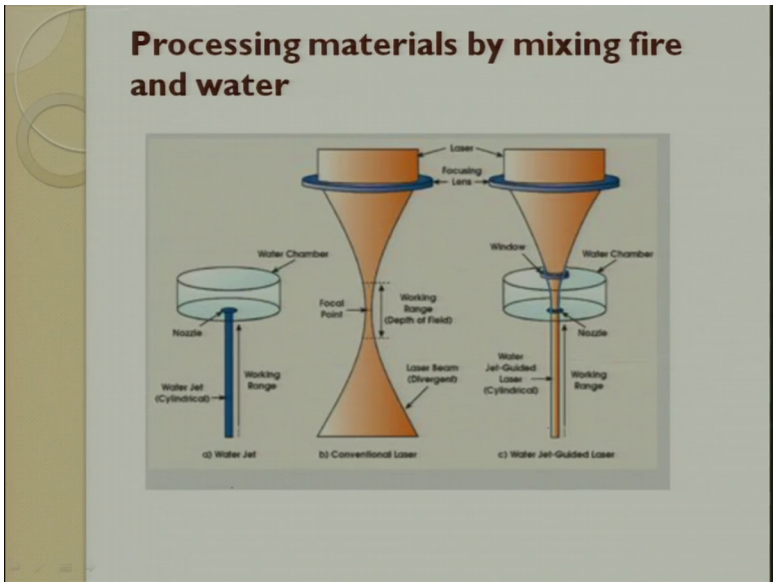

So, here if you if you see people have started doing several modifications in the laser, generally laser will have a raised profile. So, this is a working zone where you can keep the workpiece under and then the laser beam expands out or it expands. So, in order to avoid this what people do nowadays is they have start using a water jacket which is around the laser, such that the laser is always focused and it does not diverge. So, you can get a very high aspect ratio holes made in without taper. So, this is how the modifications people look at it in order to get a proper lasing action on top of the workpiece.

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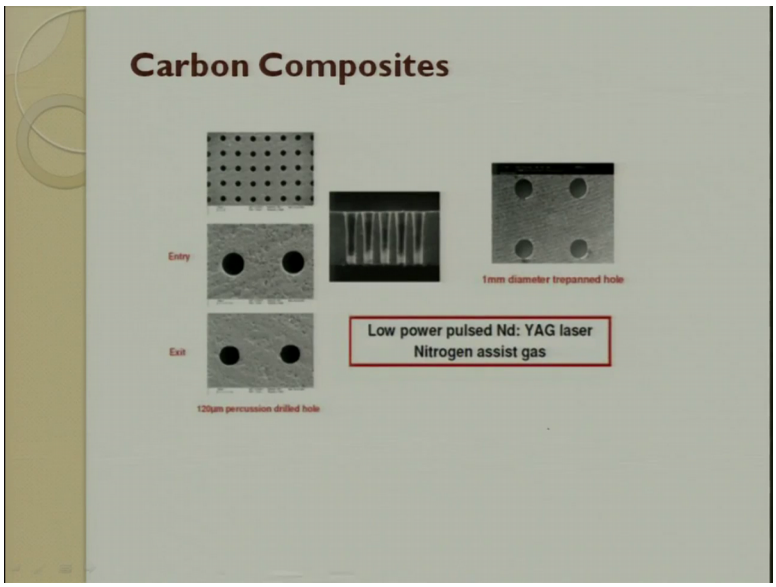

So, you can see at the entry side exit side a cross section you can always see a taper which is formed. So, depending upon the choice of the laser you can try to get good output. So, here is a display which I have made for carbon fibre composites.

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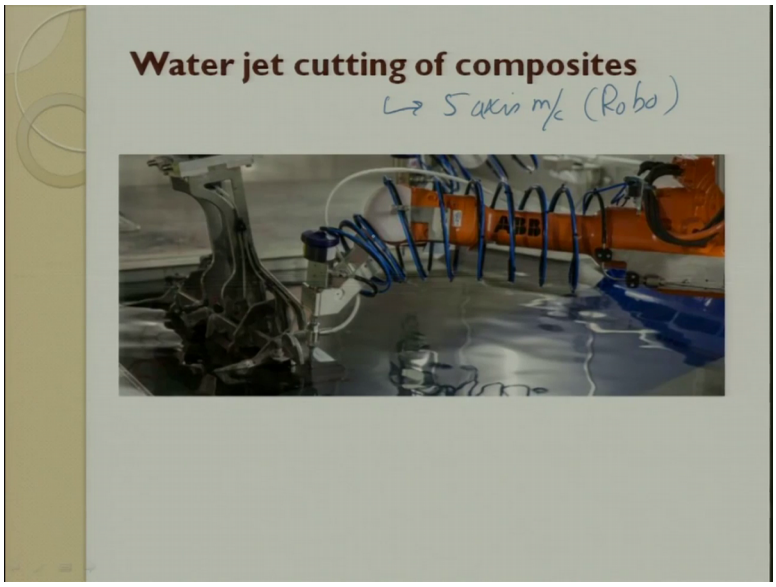

People have started using water jet and water jet also they have started using 5 axis, 5 axis machine and it is basically a Robo which is used in the hand of a Robo they have given a water jet, this water jet nozzle tries to move over a surface to make 2 D cuts.

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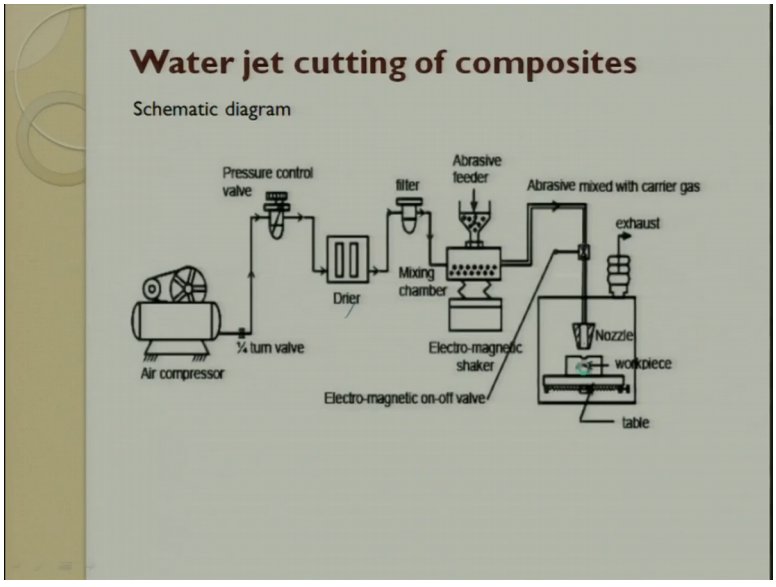

So, you will have when we talk about jet machining process I said the either the water or the abrasives are increased the velocity by adding some carrier media to; it this career media pressure gets mixed with the abrasive or water it gets pressurized and then it gets out through a nozzle and then you do a machining. So, you have an air compressor, then you have a dryer to remove the water content in air then you have a mixing chamber if you want you can bypass this or you can have this abrasives. So, the abrasive also gets mixed up with the with the air.

So, that this air is a career media abrasive they get into the nozzle. So, you use a electromagnetic valve to open and close or to control at this the through the nozzle the abrasives come out with very high pressure, which on heating the workpiece removes the material chip by chip or a piece by piece and then you try to generate the profile whatever you want.

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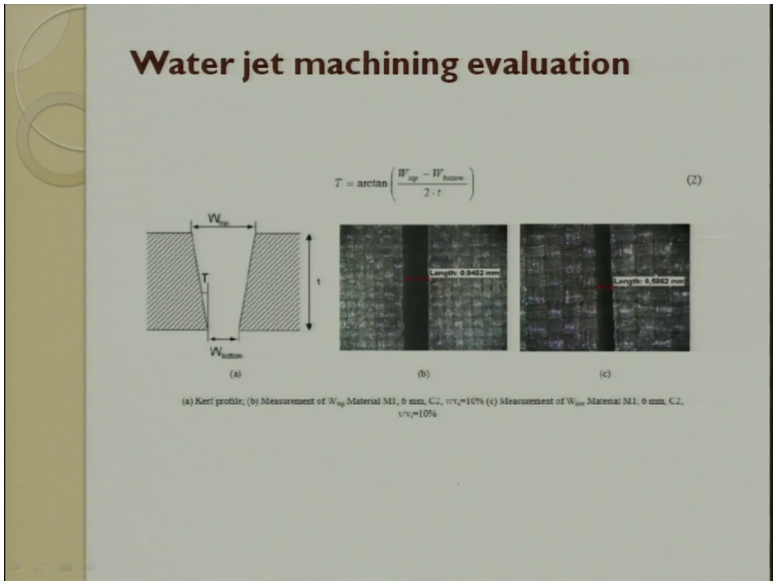

So, this is a Water jet machining. So, water jet is without the abrasives instead of this compressed air I use water and then I pressurize water by a intensifier. So, I get this. So, this is a taper like in laser you also get a taper depending upon the thickness. So, here is the equation which is return for taper. So, it is time the arc time W taper the W top minus W bottom by 2 T will give you the taper angle. So, you can see that for from the front and back which they have measured for a carbon fibre.

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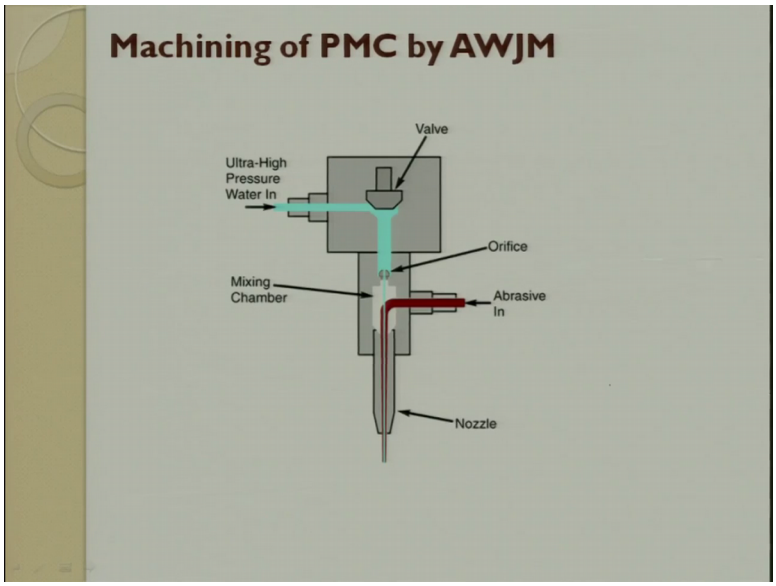

So, this is how it happens for a abrasive water jet machining. So, basically water comes in a very high pressure the there is a mixture mixing chamber. So, in this mixing chamber you can try to mix Abrasive water and then abrasive or you can try to have air and abrasive air and abrasive it is called as abrasive machining process water and air is called as water abrasive machining process. So, it comes out of the nozzle and then you tried to do a machining.

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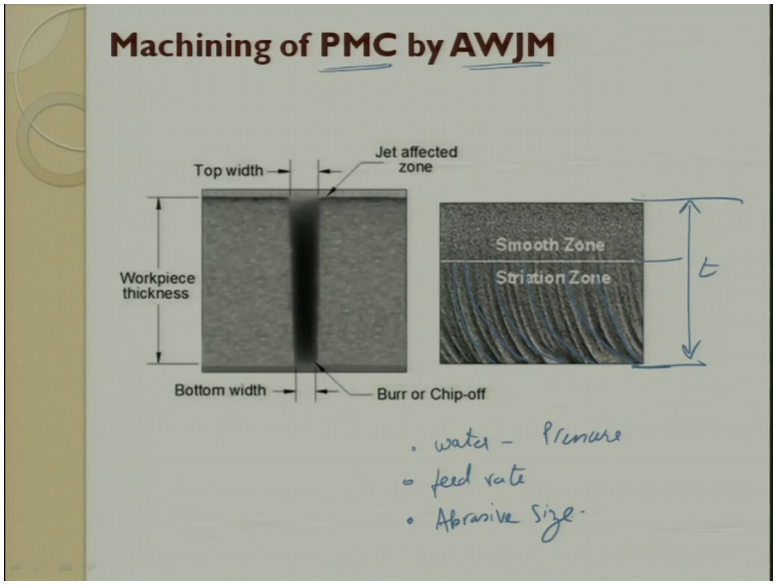

So, when you try to do abrasive jet machining of polymer matrix composite, the most important set back of this process is you will have smooth zone and you will have a striated zone. This striated zone follows the profile of the jet, whatever it flows to the workpiece. So, depending upon the thickness of the workpiece this striated zone and the smooth zone proportion varies and then you try to get a good cut. So, this in turn we will try to optimise by choosing proper parameters; the proper parameters can be water pressure or abrasive pressure jet whatever it comes then the feed rate at which the nozzle moves. So, these are the 2 important parameters on top of the abrasive size.

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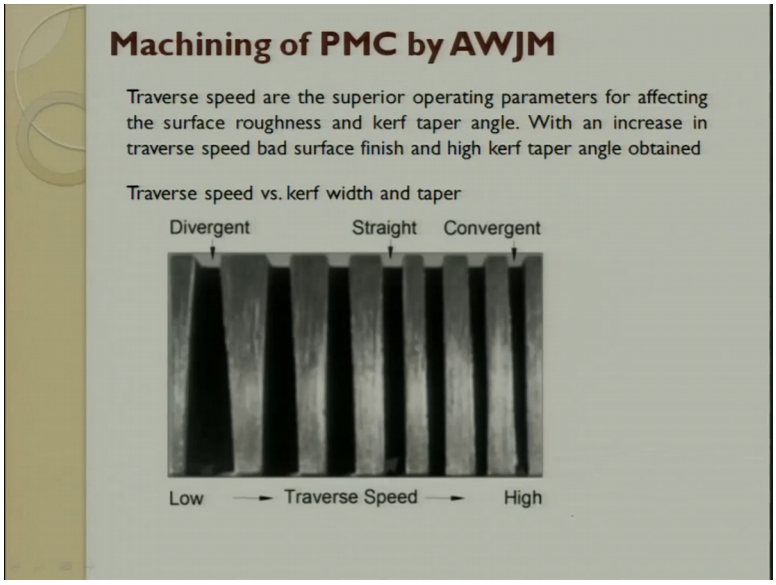

So, when you see that you can see divergence you can see divergence you can see convergence you can see straight; straight nozzles a straight channels are getting machined. So, you can this depends on the traverse speed that is a feed rate which I was talking to as and when you go higher and higher and higher you see convergent happens when divergent basically there is more time or less time for the abrasive to come hit at the workpiece and remove, we always have a convergent here, we will have divergent here and if there is a taper we always call it has a kerf width.

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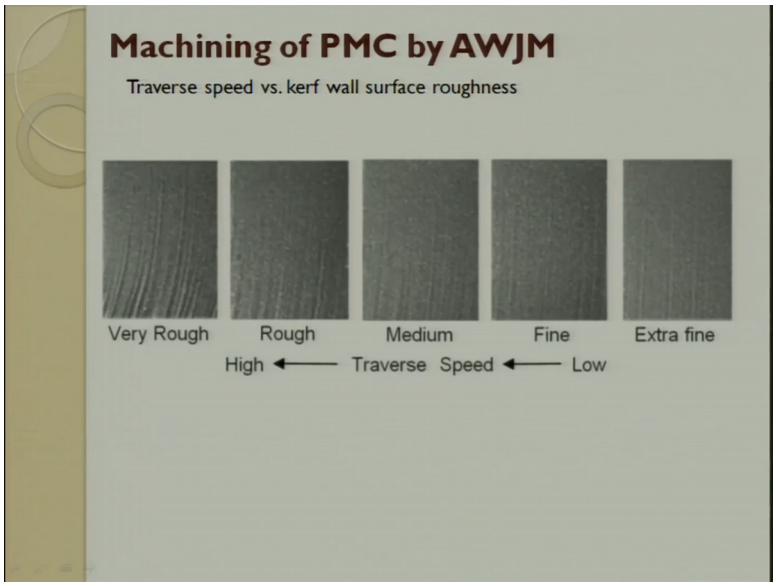

So, this is what we are talking about Very Rough surface, Rough surface, Medium rough, Fined and an Extra fine.

So, these are the surfaces which are generated by using abrasive water jet, while machining polymer matrix composite. So, in polymer matrix composite there is not much of heat. So, the response of thermoset and thermoplast will be more or less equal it will not be like in the case of heat. For example, when you use laser or when we use milling operation there will be the thermoplastics expand and contract to give the output. So, this the water jet can be used for milling.

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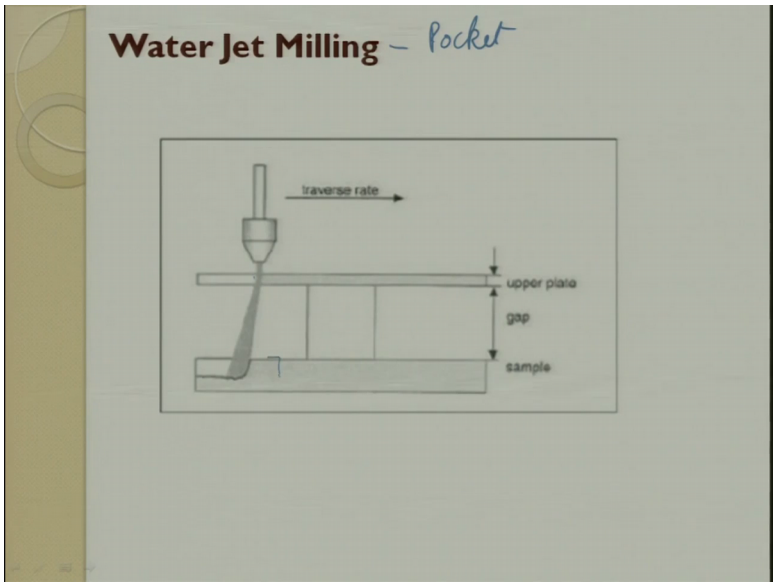

So, milling is basically what you are trying to talk about is to make pockets till now what we were seeing is only cutting. So, cutting means through to through cutting now what we are trying to talk about is how do you mill a surface to get the required output.

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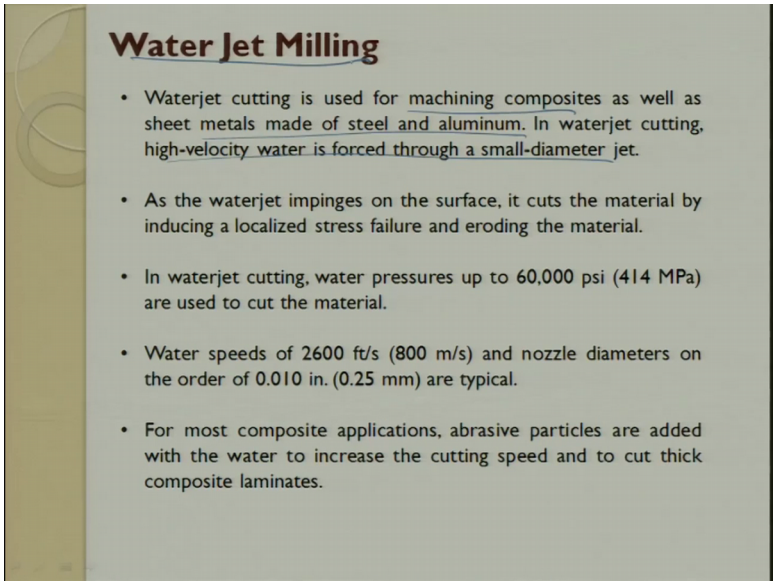

So, water jet milling. So, here the water jet cutting is used for machining of composite as well as sheet metals made out of steel and aluminium the water jet cutting has a high velocity water is forced through a small jet.

So, it then if you try to move the jet and make sure that it does not does a through cut.

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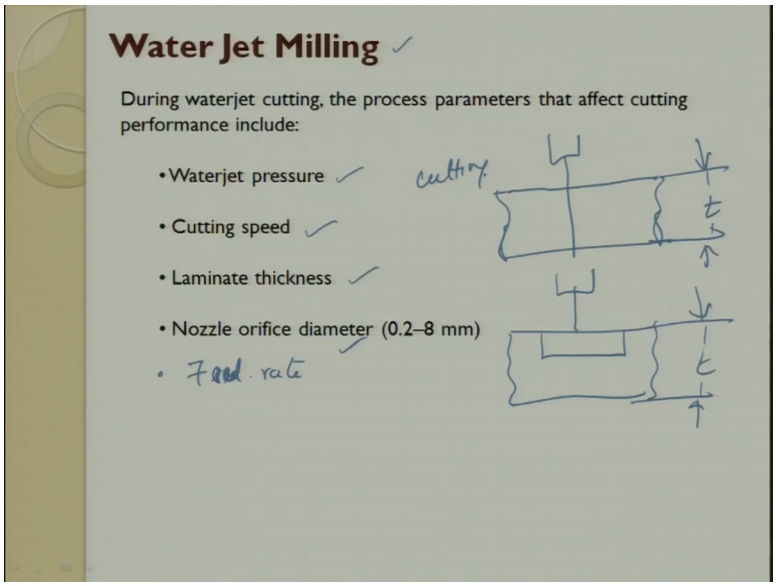

So, then it is more or less called as a abre or it is called as water jet milling. So, in water jet cutting the process parameter that affect the cutting performance are going to be pressure speed laminate thickness and nozzle diameter, when it goes to water jet milling the feed rate feed rate place a very important role and the feed rate is plays a very important role. So, you do not allow a through cut to happen and get the required output.

So, what are you trying to say suppose if this is the workpiece and this is your t. So, if you have a nozzle and through the nozzle if it is done this is called as cutting, when you have the same thing this is your t, what have you done is you have the feed rates have increased and you do not give enough of time for to make a through cut. So, these are called as water jet milling. So, the feed rate is one parameter which is very important you do it.

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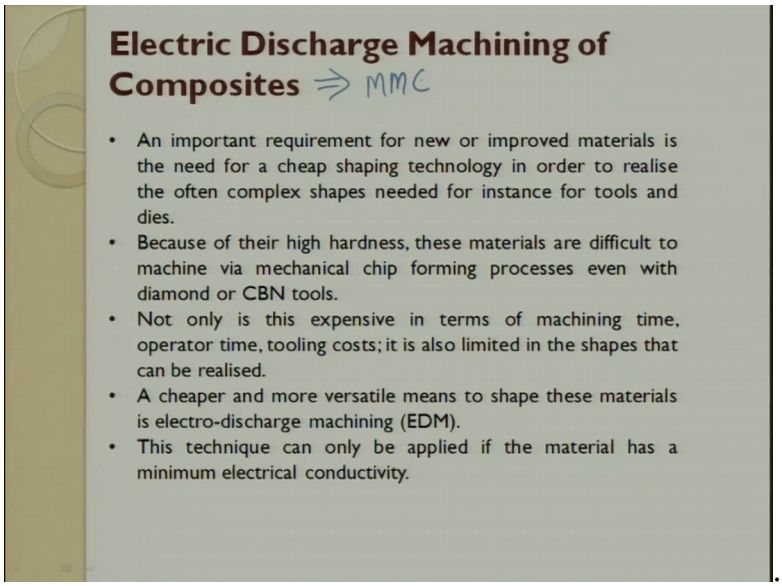

So, electric discharge machining of composites are possible wherever you want to do a metal matrix composite. So, there has to be a metal to finish the circuit.

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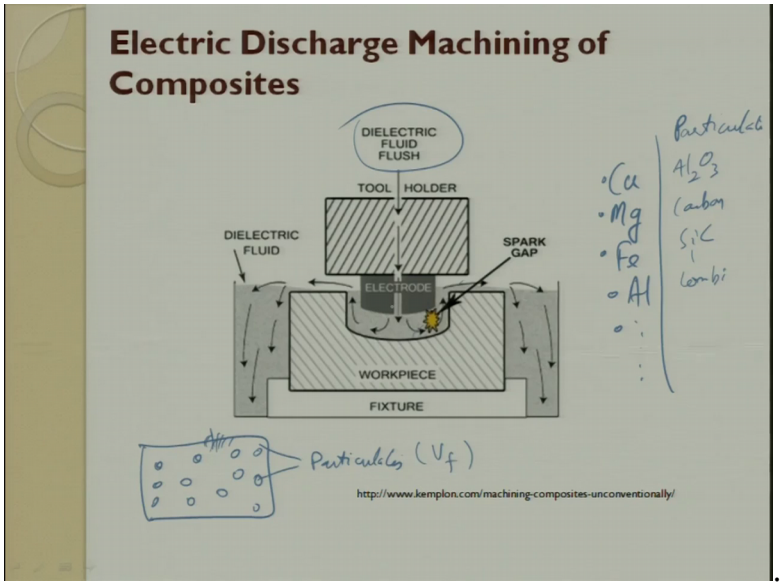

So, this is more predominant for metal matrix composite today people make copper based, people make magnesium based, people make ion based, people make aluminium based, and then etcetera. These are the matrices which people are nowadays using in a big way and the particulates when I say metal matrix composite the particulate is always a the particulate composites are used. So, this they are alumina carbon; that means, to say

graphite, SIC or a combination is used and then they make the workpiece. To here since there is lot of heat which is the between the electrode and the workpiece there is a spark going to happen. So, there is a temperature phenomena so here it is heat is applied and then there is a subtraction process which happens here. So, here it is pretty interesting because in metal matrix composite, you will have reinforcing agent also there if the matrix melts these are the particulates.

So, if the matrix melts off, then the particulates also drop. So, here depending upon the volume fraction you choose a proper process parameter and then you try to do. So, since there are lot of particulates coming up and then small small buds coming out. So, the flushing becomes a very very so here, since the particulates are more depending upon the volume fraction if the volume fraction is very high number of particulates are more if the particulates are more matrix is less if the matrix is less the melting happens of the matrix. So, particulate also falls down. So, there will be lot of burse which is there in the cutting zone. So, these burse have to be ejected out. So, we always use a dielectric to flush this burse out and so when you say this dielectrics can flow from the side or through the tool to get the to remove these burse and so from the cutting zone.

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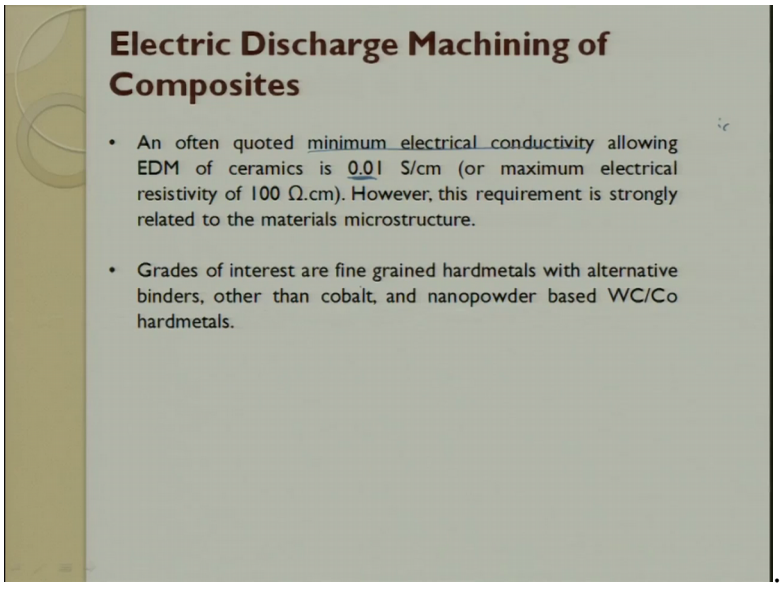

So, this is predominantly used for metal matrix composite and of course, if you can make a ceramic matrix composite conductive. So, then that is also used for machining. So, I have put down the properties which are there. So, minimum required electrical

conductivity of the idiom of a ceramic if you want it has to be **point 0** point 0 1 Siemens per centimetre square. So, if you have that then you can start doing the machining.

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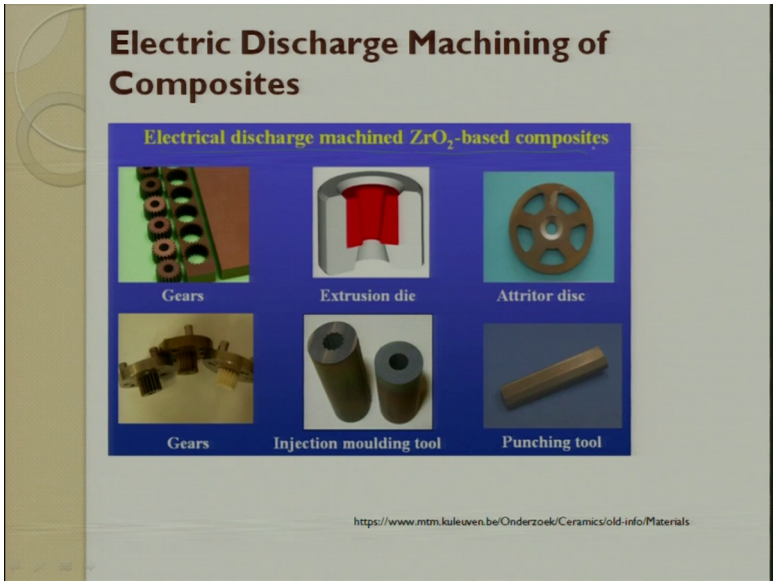

So, these are some of the electric discharge machine zirconium oxide based composites. So, these are some of the things which are made out of it and then people are using it.

With this we will come to an end of the machining lecture. So, in this machining lecture we predominantly focused on the polymer matrix composite and then we saw different processes like conventional nonconventional how are these processes getting done and how is it helps in doing the machining of composite materials.

Thank you