Production Technology: Theory and Practice
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Lecture - 19
Water Jet Machining

Hello and welcome to the discussion sessions of production technology theory and practice course. Let me remind you that we started discussing in the last session the advanced machining processes or non-traditional machining processes. And I have told you in great details why the non-traditional machining processes are required and how they come into practice.

We need to machine very hard materials which are being provided to us by the metallurgist and the material scientists and to machine those hard materials we need to have the tool material which is much harder than the workpiece material. And for that reason, we have to use different other kinds of energies and then no more the direct contact between the tool and the workpiece happens. In the case of the non-traditional machining, we can have very high accuracy, very high finish and in many cases very high production rate also.

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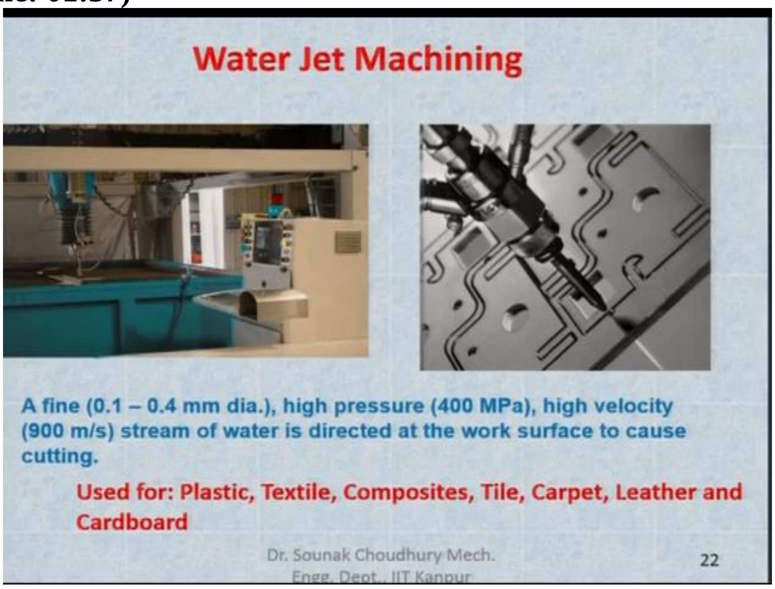

I was showing you in the last session that there is a waterjet machining; here the very fine water jet impinges the surface. And it can make a through hole within this width; you can see the width of the workpiece shown here. This is the kind of the grooves or the slots that the waterjet can machine by moving that waterjet along with this part.

Now a fine stream of water that is the 0.1 to 0.4 millimetre in diameter, so this diameter is 0.1 to 0.4 millimetre, pressure, I said already that this is up to 400 mega pascal, high pressure high velocity up to 900 meter per second stream of water is directed at the work surface to cause the cutting. This kind of waterjet machining process used mainly for plastic, textile, composites, tile, carpet, leather and the cardboard.

The waterjet machining overall was introduced to cut the cardboard, wood and that process used to be very fast with high production rate. Later that was tried on the metal as well and this is not very widely used, but this is successful, but mostly the water jet is used to process the plastic, textile, composites, tile, carpet, leather, cardboard and so on.

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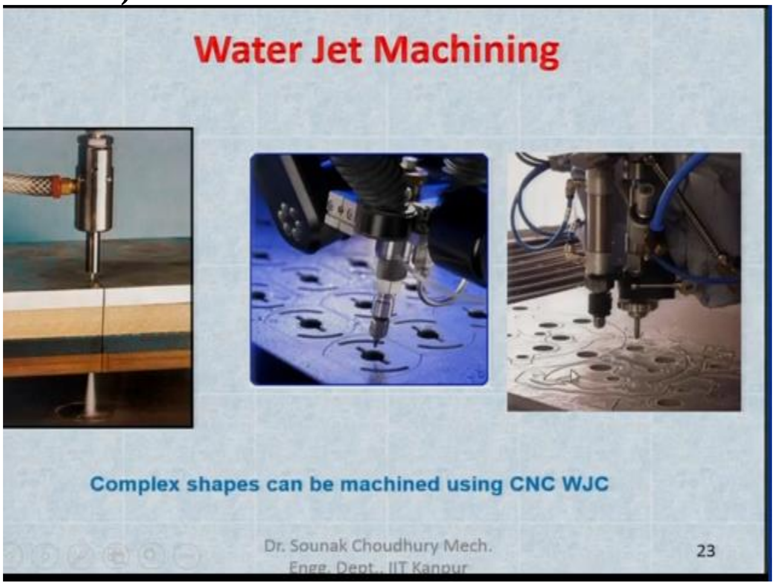

Here there are other examples. You can see that this is the thickness through which the water jet can impinge and cut. This is the wood and that the nozzle can be traversed so that the entire width can be removed. Here in other examples you can see that this is some kind of plastic material. And here the shapes are very complicated which can be machined by traversing the nozzle; this is the nozzle through which the high pressure water jet is passed.

And here there is also a very complicated path is being formed as you can see that it is by traversing the nozzle, we can also have this kind of controls.

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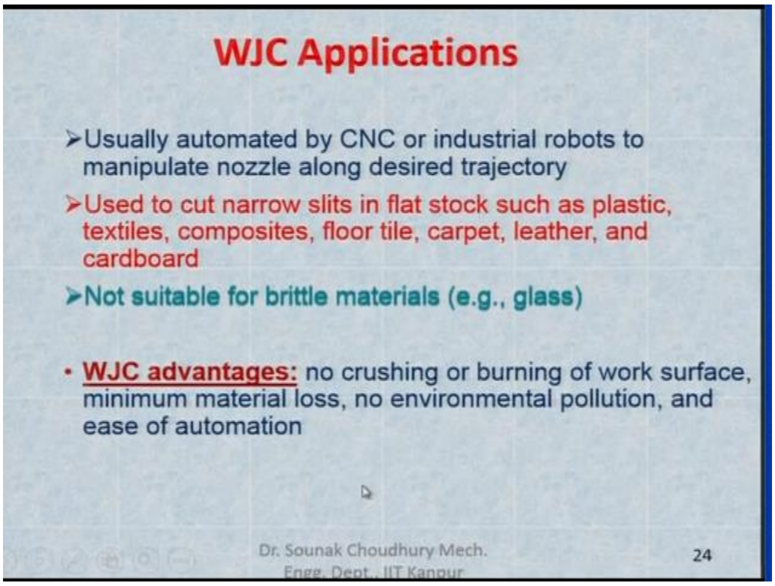

Water jet cutting applications are usually automated by the numerical control or industrial robots to manipulate nozzle along the desired trajectory. These are used to cut narrow slits in flat stock such as plastic, textiles, composites, floor tile, carpet, leather and the cardboard. Not suitable for brittle material for example, for glass, it cannot cut it because it will break and then that fracture propagates and it will not be cut with a proper accuracy and so, it is cannot be used for the glass.

So, what are jet cutting advantages that there is no crushing or burning of the work surface because there is no temperature which is involved here. Minimum material loss, no environmental pollution because nothing comes out to the environment, to the atmosphere and ease of automation because we can have the computer numerically controlled and it can be programmed so that the nozzle can be moved through a very complicated path like the tool moves in case of the computer numerical control machines.

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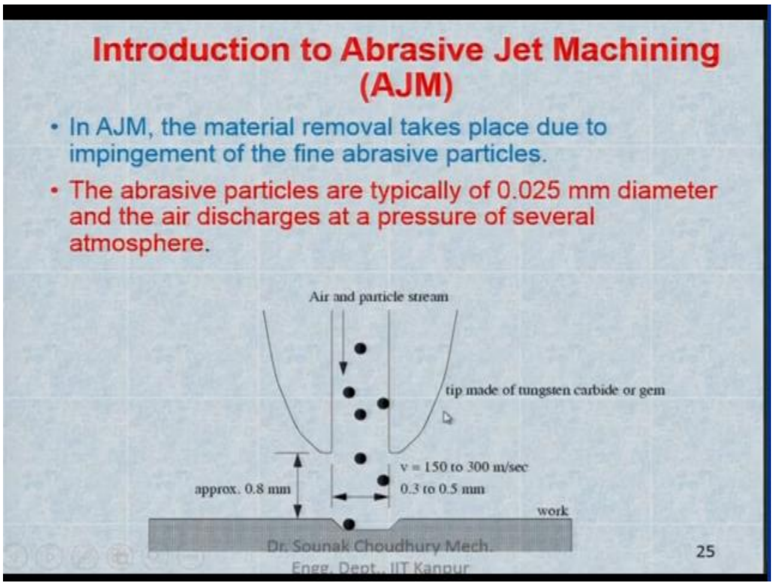

We will continue with the introduction to the abrasive jet machining. In this process the material removal takes place due to the impingement of the fine abrasive particles. Here we are talking about the abrasive jet machining. Here the plain water jet is mixed with an abrasive jet which will impinge the workpiece surface to remove the material.

The abrasive particles typically have very small diameter which is about 0.025 millimetre diameter and the air discharges at a pressure of several atmosphere. Here air in high pressure along with the abrasive particles are directed towards the workpiece and this is the nozzle this nozzle is at a distance from the workpiece approximately by 0.8 millimetre. This is this stand-off distance as I said earlier that stand-off distance is very important.

The velocity is very high which is about 150 to 300 meter per second and the nozzle diameter is about 0.3 to 0.5 millimetre. Abrasive particles are very small of 0.025 millimetre diameter. Here the disadvantage is that since the abrasive particles pass through the nozzle, it has to be of a very hard and the wear resistant material because the abrasive particles will wear out the nozzle and the nozzle can very quickly be worn out.

Therefore, the tip is made of the tungsten carbide or some kind of a gem. That is a very hard and brittle material that will not be easily worn out. And very often what happens is that the abrasive jet machining nozzles they are made into 2 parts. Made into 2 halves and they are assembled this is to replace the nozzle quickly as when it is necessary when it is worn out to a large extent and cannot be used.

Because the diameter has become much more and the jet becomes wider or the higher in diameter as you understand then the desired quality cannot be achieved. In that case, the 2 halves are opened and then they can be changed. Very often there is a layer inside this so that or there is another cylindrical surface inserted here so that surface or bushing as we call it that can be replaced.

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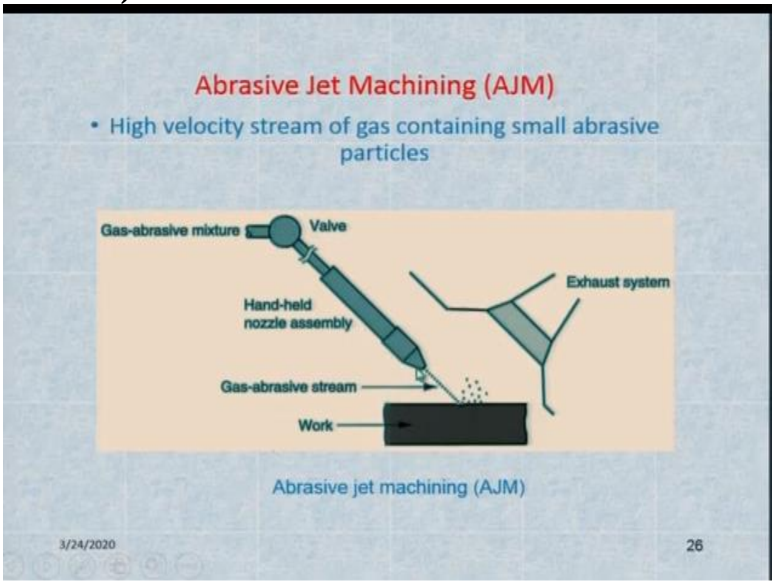

Abrasive jet machining: here the high velocity stream of gas containing the small abrasive particles is used. This is schematically shown here, this is the workpiece this is the gas abrasive mixture, here this is the handheld nozzle assembly and that nozzle assembly is kept at a certain distance from the workpiece and this is the stand off distance that we said. This can be kept at an angle that depends on what kind of material you were using.

This angle can be calculated at which the material removal rate is maximum and there we have the exhaust system. That high pressure with the gas when it is impinging the workpiece along with the workpiece material this can be sucked, so there is a vacuum created and this material along with the abrasive can be sucked. This is the gas abrasive stream which comes and this is the material along with the abrasive material or the work material together they can go through the exhaust system.

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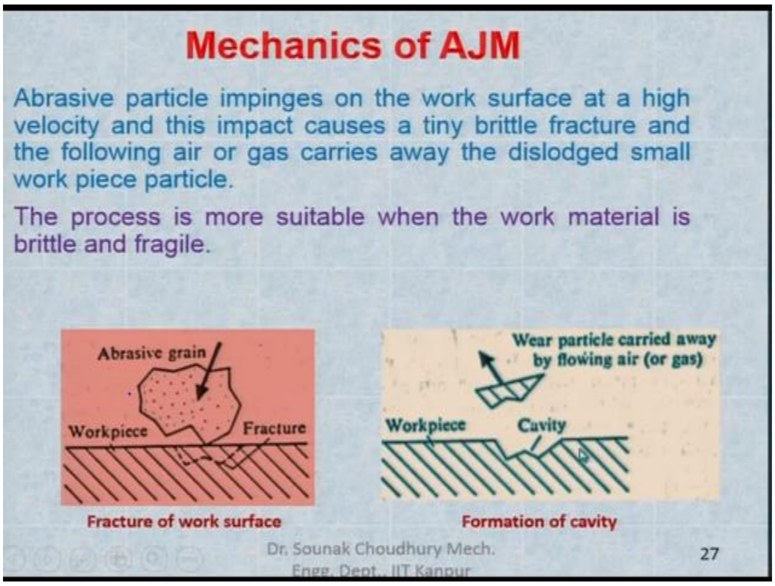

Mechanics of abrasive jet machining: as we said that this is a brittle fracture, now the abrasive particles impinge on the work surface at a high velocity. And this impact causes a tiny brittle fracture here. Here is the gas carries away the dislodged small work particles. This is the work particle this is carried away by the flowing air because this is coming with the gas that we said and this can be sucked by the exhaust system.

The process is more suitable when the work material is brittle or fragile because it is a brittle fracture; as you can see that this abrasive grain impinges the surface it makes a fracture on the surface and a tiny area of the material is removed from the workpiece surface this is the way the cavity is formed all over the place where it is required.

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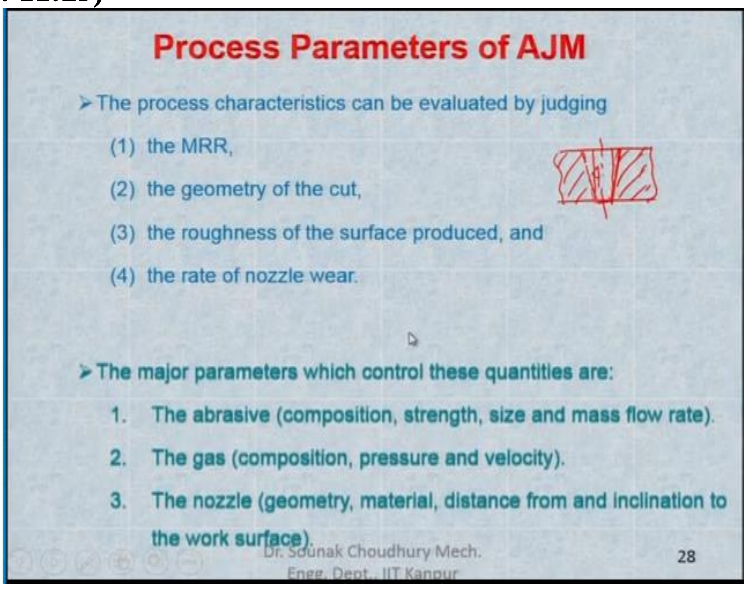

The process parameters of abrasive jet machining: the process characteristics can be evaluated by judging the material removal rate, the geometry of the cut, the roughness of the surface produced and the rate of nozzle wear how the process is going how much is the material removal rate, what is the geometry, like as we said that suppose we have to make a hole, so whether it is absolutely straight hole or it is a little tapering.

What is the quality. Let's say this is the workpiece and we have to make that hole and it has to be absolutely straight, but sometimes we can see that it can have a tapering. This will define what is the process characteristics, the roughness of the surface produced, inside the hole what will be the roughness here. The rate of nozzle wear, about the nozzle wear I already said that this has to be replaced often because the abrasive particles wear out the nozzle.

Therefore, less the nozzle wear, better will be the process characteristics, the process life is more. The major parameters which control these quantities are the abrasive; what is the composition of the abrasive. Strength, size, mass flow rate are the parameters. Now the gas has the composition pressure velocity which can be regulated, pressure velocity is normally regulated.

The nozzle, that is the geometry of the nozzle, what is the material and the distance from and inclination to the work surface this is the stand-off distance and at which angle the nozzle has to be directed. These are the major parameters that will control the quality of the machining.

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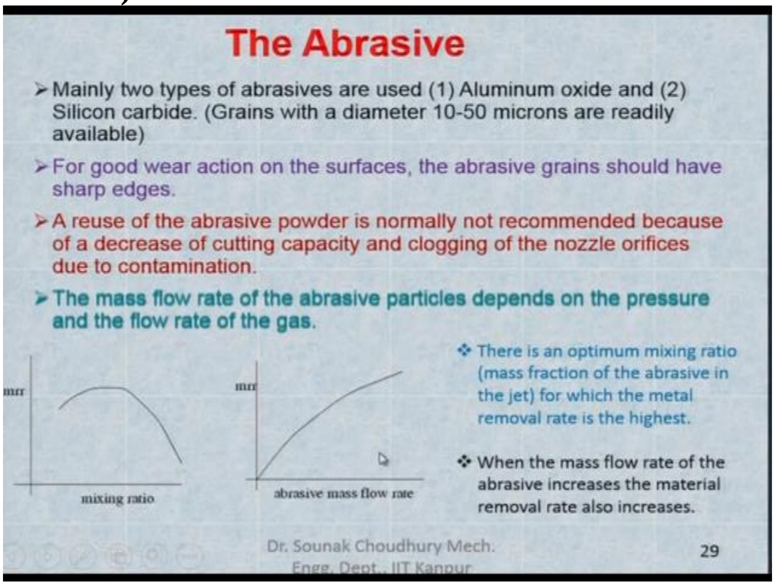

The abrasive: mainly 2 types of abrasive are used, namely aluminium oxide and the silicon carbide. These grains are of very small diameter, about 10 to 50 microns, they are readily available. For good wear action on the surfaces the abrasive grains should have the sharp edges. A reuse of the abrasive powder is normally not recommended because they are already worn out, decrease of the cutting capacity and clogging of the nozzle orifices due to the contamination.

Therefore, normally that abrasive powder which has already been used once is thrown out because in those abrasive particles each of the grains will be worn out. Their cutting ability will be less and they will consume more power with rubbing and all without having the proper quality or the proper accuracy and the quality of work piece. The mass flow rate of the abrasive particles depends on the pressure and the flow rate of the gas.

In the slide here these are the two curves which have been made from the experimental results and this is the qualitative curve like this is the material removal rate on the Y axis and the mixing ratio on the X axis and here is the abrasive flow rate. There is an optimum mixing ratio which is the mass fraction of the abrasive in the jet for which the material removal rate is maximum as you can see here. By mixing ratio you understand that this is the mass fraction how much the mass of the abrasive material in the jet.

When it is not very high in that case the material removal rate will be less, but if it is more dense, then you understand that material removal rate will be again less because it will clog it will not pass through very easily because it is very dense. So, there has to be an optimum value of the mixing ratio of the mass of the abrasive grains, the mass fraction. Another curve that shows that as the abrasive mass flow rate is more, the material removal rate increases, it is not linearly increases.

But it is nonlinear, when the mass flow rate of the abrasive increases the material removal rate also increases. These are experimental curves but the physics is very well understood that as flow rate will be more then the material removal rate increases and it can be shown theoretically that dependence of the MRR with the materiel removable rate, with the abrasive flow rate is a nonlinear curve.

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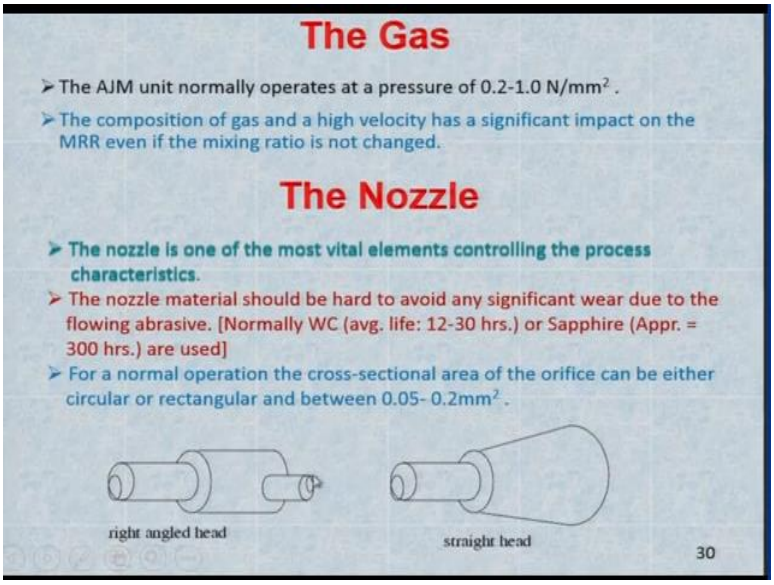

The abrasive jet machining unit normally operates at a pressure of 0.2 to 1 Newton per millimetre square. The composition of gas and the high velocity has a significant impact on the material removal rate even if the mixing ratio is not changed. That means the composition of the gas is important and the gas velocity, these two factors will have the effect on the material removal rate.

The nozzle: the nozzle is one of the most vital elements controlling the process characteristics. The nozzle material should be hard as I said because otherwise it will wear out very easily since the abrasive particles flow through that. The nozzle material should be hard to avoid any significant wear due to the flowing abrasive. Normally the tungsten carbide material is used the average life is 12 to 30 hours.

Or sapphire is used. Sapphire is a gem and the sapphire is very expensive; this is a stone or a gem and this is a very hard material, but more importantly that material is very difficult to machine. To make a nozzle out of sapphire itself is difficult. But if it can be made and when it is made by sapphire, the life is very high because it is a very hard material and you can see that life can be up to 300 hours.

In comparison to tungsten carbide, also we know that tungsten carbide is very hard material, but the average life is not more than 12 to 30 hours, but in case of sapphire it is above 300 hours. For a normal operation the cross-sectional area of the orifice can be either circular or rectangular and between 0.05 to 0.2 millimetre square. This will be the cross sectional area of the orifice through which these flow holes pass.

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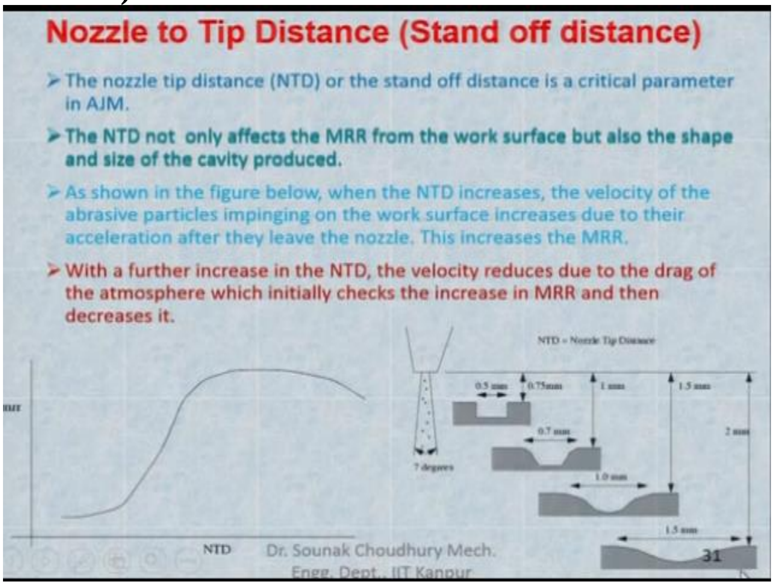

Now the nozzle tip distance is the stand-off distance and I already told you that the nozzle tip distance or the stand-off distance which is the distance between the workpiece and the nozzle tip is very important to maintain the quality of the machined surface. The nozzle tip distance or the stand-off distance is a critical parameter in the abrasive jet machining. The nozzle tip distance not only affects the material removal rate from the works surface, but also the shape and size of the cavity produced.

This I already explained to you that material removal rate will be affected by changing the nozzle tip distance also the quality will be affected, quality in the sense that shape and size of the cavity that is being made. As shown in the figure, we can see that when the nozzle tip distance is increasing, the velocity of the abrasive particles impinging on the work surface increases due to their acceleration after they leave that nozzle; this increases the material removable rate.

Once again, when we are increasing the nozzle tip distance here it is shown that the velocity of the abrasive particles on the work surface increases due to their acceleration after they leave the nozzle. Therefore, in this case this shape that we are getting with an appropriate let us say nozzle tip distance this shape gets deteriorated as the nozzle tip distance increases and this increases the material removal rate.

With the further increase in the nozzle tip distance, the velocity reduces due to the drag of the atmosphere which initially checks the increase in MRR and then it decreases. This is the curve which can be drawn showing that when the nozzle tip distance is increasing, initially the material removal rate increases, but after that it stabilizes and then falls. Here you can see the entire nozzle tip distance, different nozzle tip distance is given and for which the perfect one is made 0.7, 0.5 millimetres and if it is increasing like that, it will have the distortion.

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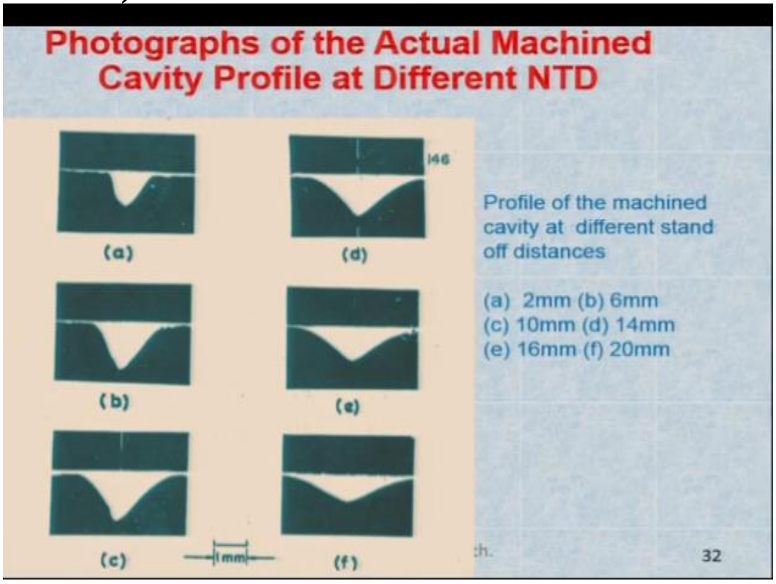

This is the actual photograph of the actual machined cavity profile at different nozzle tip distance. From a to f here you see starting from 2 millimetre to 20 millimetre and when the nozzle tip distance is less than the required one then the energy is not sufficient. So, the cavity cannot be made properly. When the energy is increasing, energy of these impinging particles will be increasing, then the profile will be made in a better way.

At the optimum value of the nozzle tip distance the quality of the machined surfaces is the best and as the nozzle tip distance increases, the energy becomes less because it is losing that in the air and then there will be inaccuracy in the machining.

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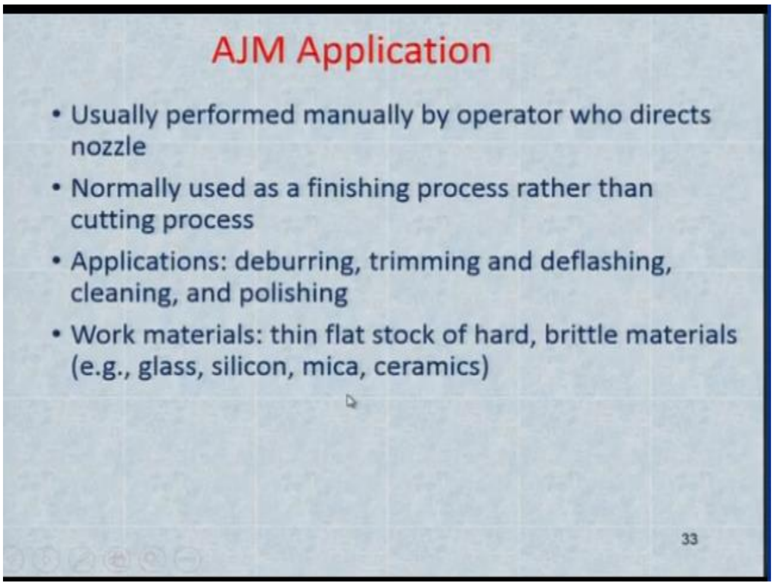

Application - where the abrasive jet machining process is applied. Usually performed manually by operator who directs the nozzle and traverse it manually, normally used as a finishing process rather than cutting process. It is For cutting process, as I said, it is the waterjet machining that is most popularly used but abrasive jet machining is used more for finishing operation so that the required surface roughness can be obtained.

Applications like deburring, that is removing the burrs, trimming and deflashing, deflashing is that when you have the flash after the stamping operation for example that can be removed very easily and effectively by the abrasive jet machining, cleaning and the polishing of the material particularly after casting; cleaning is very important because surface is not very fine.

Work materials: thin flat stock of hard, brittle materials, glass, silicon, mica, ceramics they can be used as the work material and the abrasive jet machining can be used to remove material from them.

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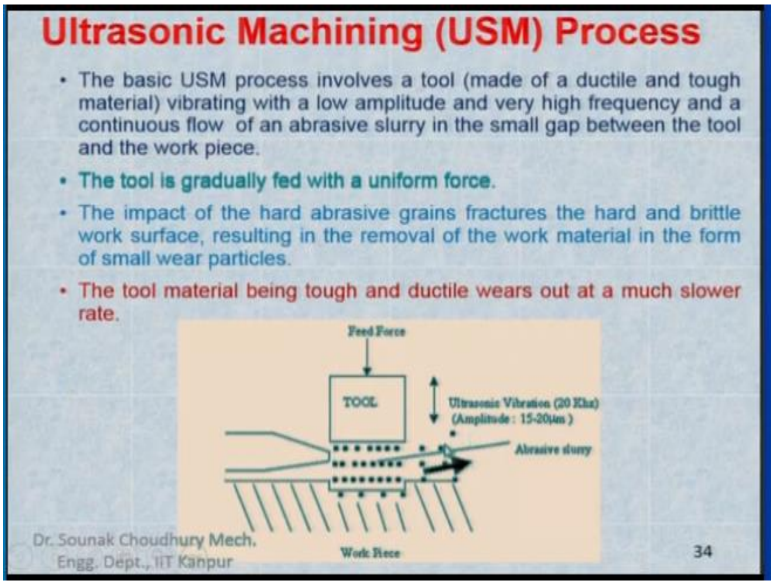

Next process is called the ultrasonic machining. Initially I said that by name itself it indicates that it is the machining process where the ultrasonic frequency is used which is a very high frequency, it can be more than 25 kilo hertz. The basic mechanism basic USM that is the ultrasonic machining process involves a tool made of a ductile and tough material.

Here in the line diagram you can see that this tool is made of a ductile and a tough material vibrating with a low amplitude and very high frequency; frequencies here it is said up to 20 it can go up to 25 Kilo hertz also. Amplitude here as you can see, that it is 15 to 20 micron which is low amplitude and very high frequency 20, 25 kilohertz and a continuous flow of abrasive slurry.

There is a nozzle through that the abrasive slurry that is the stream of abrasive material is passed and the tool vibrates. This stream of abrasive material is passed through the gap between the tool and the workpiece which is the stand-off distance. The tool is gradually fed with a uniform force towards the workpiece because the workpiece material is removed here and the stand-off distance is changing.

To maintain that stand-off distance, the tool is given a feed force and depending on how much workpiece is being removed the tool moves accordingly towards the workpiece with a particular feed. This arrow shows that this is the way the tool vibrates with very low frequency. It cannot be seen even with the open eyes and it has a very high frequency of 20, 25 Kilo hertz.

The impact of the hard abrasive grains fractures the hard and brittle work material, this work material is hard and brittle resulting in the removal of the work material in the form of small wear particles and these wear particles can be taken away by suction. The tool material being tough and ductile, wears out at a much slower rate than the workpiece because as you understand that these abrasive materials or abrasive particles also impinge the tool, but it will impinge after it rebounds from the workpiece.

Therefore, the frequency and the amplitude are given by the tool this is imparted on each of these particles and those particles then with that frequency and with that amplitude impinge the surface and it is a brittle surface and hard material. This will break or it will have a brittle fracture and the fractured material will be removed from the surface.

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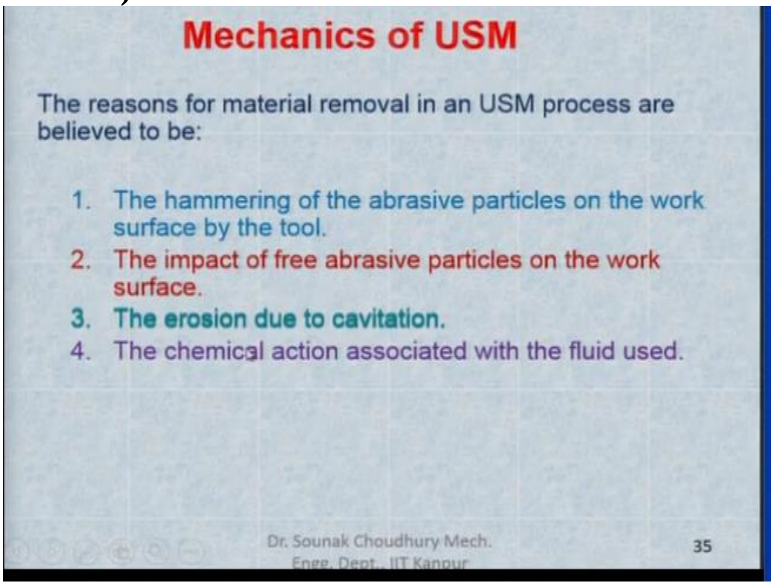

Mechanics of ultrasonic machining: the reasons for material removal in an ultrasonic machining, which is the mechanics of the process, are believed to be, one is the hammering of the abrasive particles on the work surface by the tool. Here we have the abrasive particles this is being hammered, because the tool is imparting certain vibration to each of these particles that is one, the impact of free abrasive particles on the work surface is the impact.

The erosion due to cavitation: and this cavitation means that the material is particularly caveated in the space here, so this creates the erosion of the material, the chemical action associated with the fluid used. These are the different reasons that are to some extent or to a large extent, one of them or few of them together, can be considered as the mechanics of ultrasonic machining.

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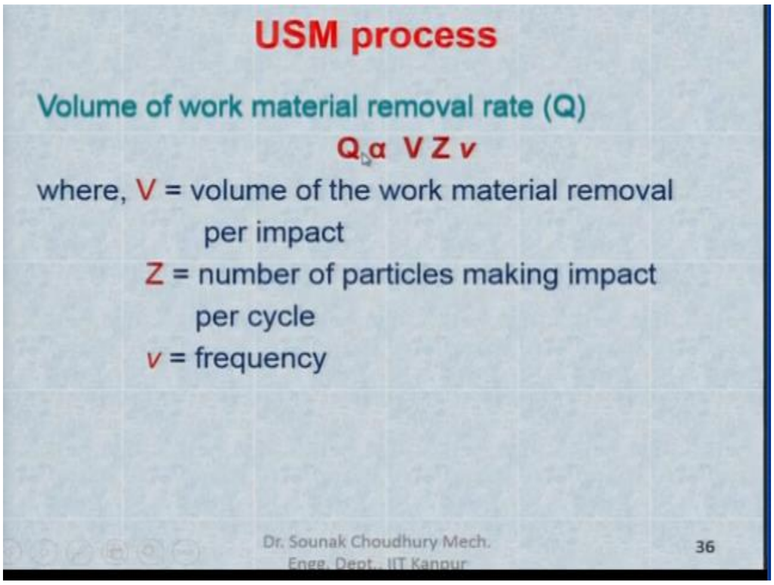

In ultrasonic machining process, the volume of work material removed, Q will be proportional to basically 3 factors, one is the volume of the work material removal per impact, this is let us say V. Next is the number of particles making the impact per cycle. More the number more will be the material removal rate. Finally, if the frequency is more, in that case the material removal rate will be more.

Therefore, the volume of work material removal rate depends on the volume of the work material removal per impact, the number of particles and the frequency.

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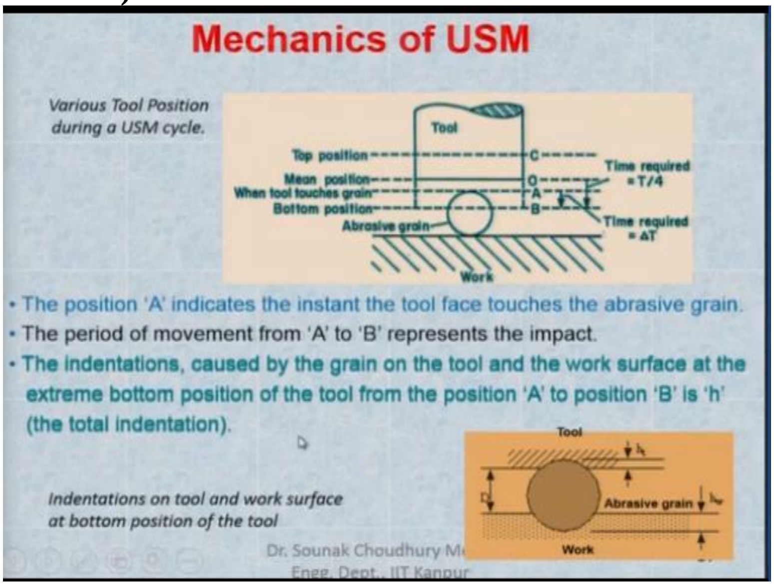

This is the diagram we will not go into very details, but this diagram is necessary to understand for assessing how much work material will be removed. To simulate the process and you want to have the maximum material removal rate or an optimum material removal rate or the optimum parameters, it is required.

In that case, you can go for the simulation for which you find out what is different tool positions, there is a mean position when the tool touches the grain that means in between the tool and this in the stand-off distance.

The position A indicates the instant the tool face touches the abrasive grain. The period of movement from A to B then it is moving along with this to the B. this represents the impact A to B when the tool is moving along with the abrasive grain.

Then it will have an impact,. The indentations caused by the grain on the tool and the work surface at the extreme bottom position here of the tool from the position A to position B is h. This position from here to here this is the bottom position this is h this will be the indentation, so this is the h and this much indentation is made when the tool is moving from A to B and this is the bottom position.

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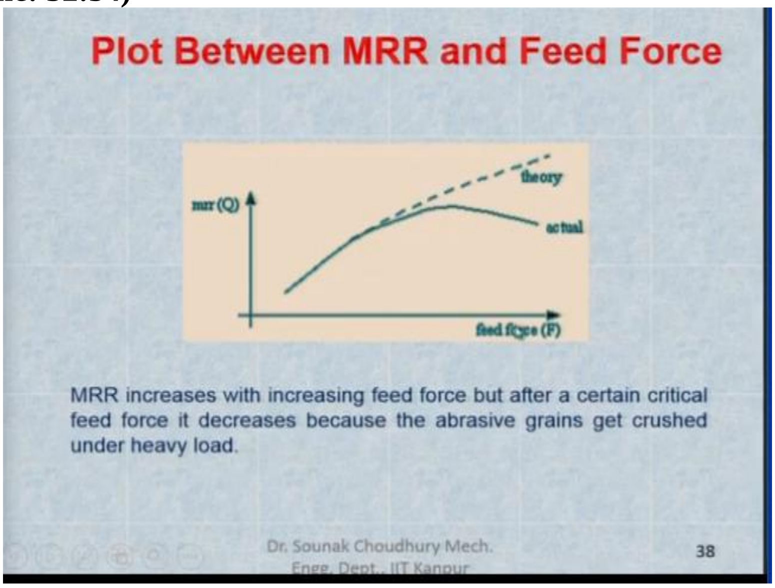

If we now plot the material removal rate and the feed force, we will get a curve as shown in the slide. Theoretically as the feed force is increasing, the more material will be removed because the volume of each particle will be more in that case and according to this equation, if the V is more in that case, the Q which is the material removal rate will be more. Therefore it will grow like that and theoretically it will be that when the feed force is increasing, the material removal rate grows.

But when the feed force is increasing that means, more force is required to move the particle. We said that the particle the tool is touching that grain and then it is moving here. So, more feed force is required so that material removal rate grows, but as it is increasing beyond a certain level, the force is high on the grain and the grain may crush.

In that case, its impact capabilities decrease that means it will not have the proper impact and it will not have the removal of the material. In that case this is the curve which happens actually. MRR increases with increasing the feed force, but after certain critical feed force, it decreases because the abrasive grains get crushed under the heavy load because the feed force is increasing, has become too high.

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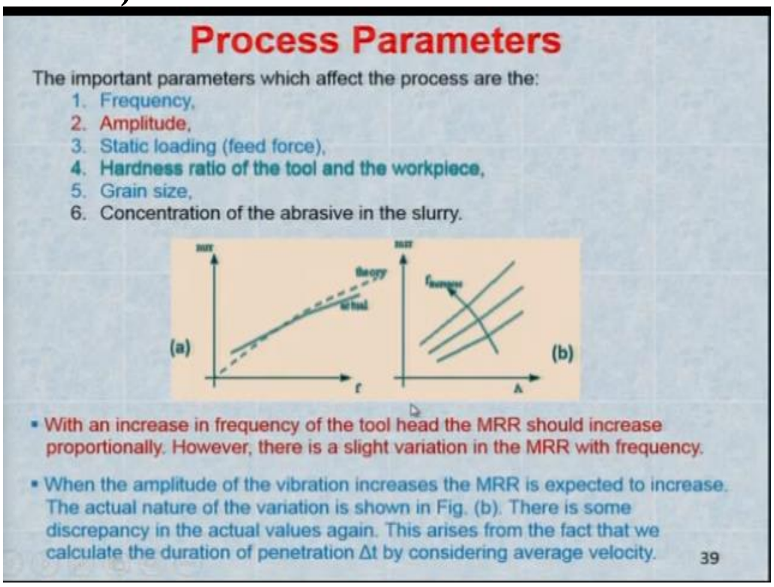

And now about the other process parameters in the abrasive machining processes. These are the frequency, amplitude, static loading which is the feed force, hardness ratio of the tool and the workpiece, grain size, concentration of abrasive in the slurry and so on and these are the curves which show what is the relationship between the frequency, amplitude and the material removal rate here is the same thing that this is the actual I already told you the reason that this is the actual curve and the theoretically it should have been a straight line.

And as the frequency increases, in each of these curves you can see that first of all as the amplitude is increasing material removal rate is increasing. But, more material removal rate we will get as the frequency is increasing; here the frequency is less than here. Here this curve is made with the higher frequency than this and this. Here the same thing is written in the slide that with an increase in the frequency of the tool head, the material removal rate should increase proportionally, as per theory.

However, there is a slight variation in the material removal rate with the frequency I explained it to the reason earlier also. When the amplitude of the vibration increases in the second curve, the material removal rate is expected to increase. The actual nature of the variation is shown in figure b, this is the actual nature. There is some discrepancy in the actual values again. This is not exactly straight line.

This arises from the fact that we calculate the duration of penetration Δt by considering the average velocity and not the instantaneous velocity, that is why it is not stated but it is a very small inclination and this can be in some cases it is not for high frequency, here these are almost straight lines, but here it is a discrepancy because the frequency is low.

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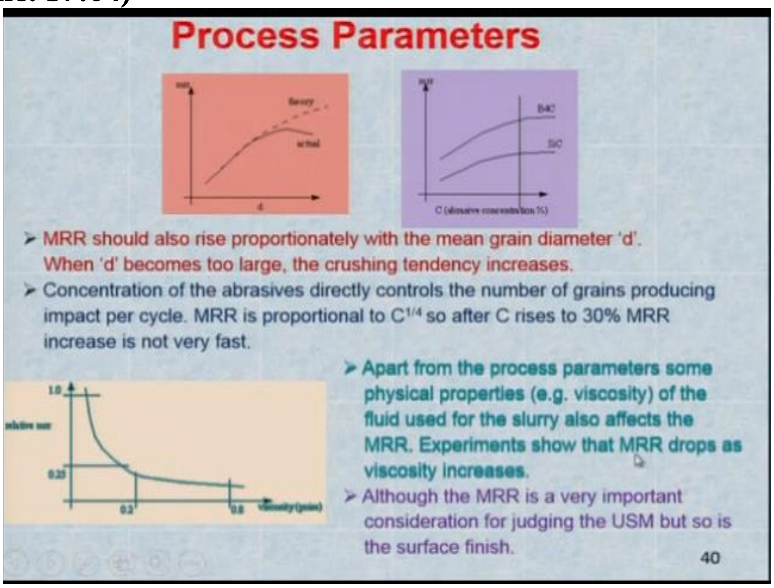

I have already explained to you that with the diameter MRR should also rise proportionally, with the mean grain diameter and this is similar to this. The feed force and MRR. Reason is the same that they get crushed, crushing tendency increases. The concentration of the abrasives directly controls the number of grains producing impact per cycle. By concentration we means that how much grain is present per unit volume of the fluid or the jet.

MRR is proportional to $C^{\frac{1}{4}}$, after C rises to 30% , MRR increase is not very fast, it almost stabilizes and this is made for the average of concentration percentage C. This is made for two different abrasive materials, namely boron carbide and the silicon carbide and the material removal rate for boron carbide will be more than the silicon carbide as you can see here.

And this stabilizes because this is also empirical relationship that the $MRR \infty C^{\frac{1}{4}}$ Therefore, it stabilizes after some time. concentration of that is what it is being already explained. Apart from the process parameters, some physical properties for example, the viscosity; the curve shown here that as the viscosity is increasing, what happens to the relative material removal rate. By viscosity of the fluid I mean to say the slurry which also affects the MRR.

Experiments show that material removal rate drops as the viscosity increases, you understand that there the fluid will be moretherefore, material removal rate will be less. Although the material removal rate is a very important consideration for judging the ultrasonic machining, but so is the surface finish in case of ultrasonic machining.

But the surface finish also is similarly important along with the material removal rate that gives you the production rate mostly and surface roughness because these are the precise parts which are being made by the ultrasonic machining. Therefore, the surface roughness is very important.

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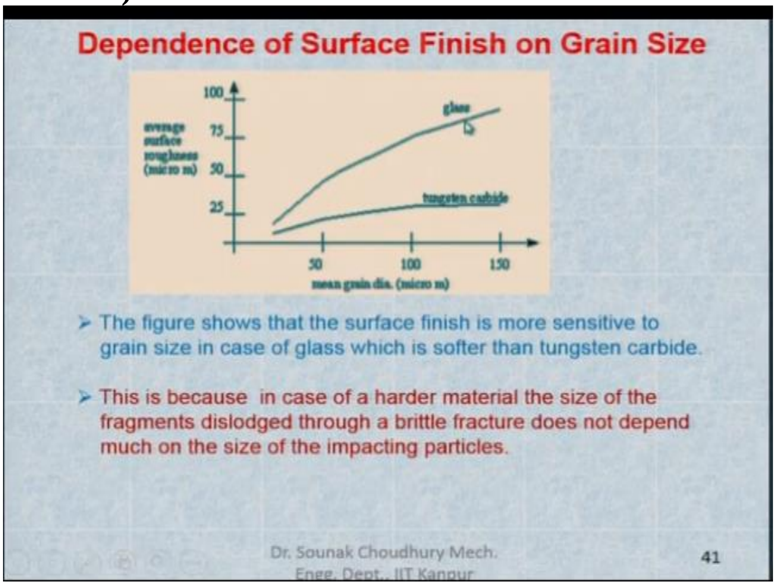

Dependence of the surface finish on the grain size: let us say for tungsten carbide and the glass material mean grain diameter we have taken in micron from 50 to 150 experimentally and this is how the curve looks like. It shows that the surface finish is more sensitive to grain size in case of glass because in case of tungsten carbide you can see the curve is not very steep. Therefore, it is more sensitive in case of glass which is softer than the tungsten carbide, that is why this falls in this way.

This is because in case of a harder material, the size of the fragments dislodged through a brittle fracture does not depend much on the size of the impacting particles. Let me explain it to you once more what happens. We are saying that the glass is more effective on this. This is because in case of a harder material the size of the fragments dislodged through a brittle fracture is independent of the size of the impacting particles whether it is a bigger or a smaller it does not matter.

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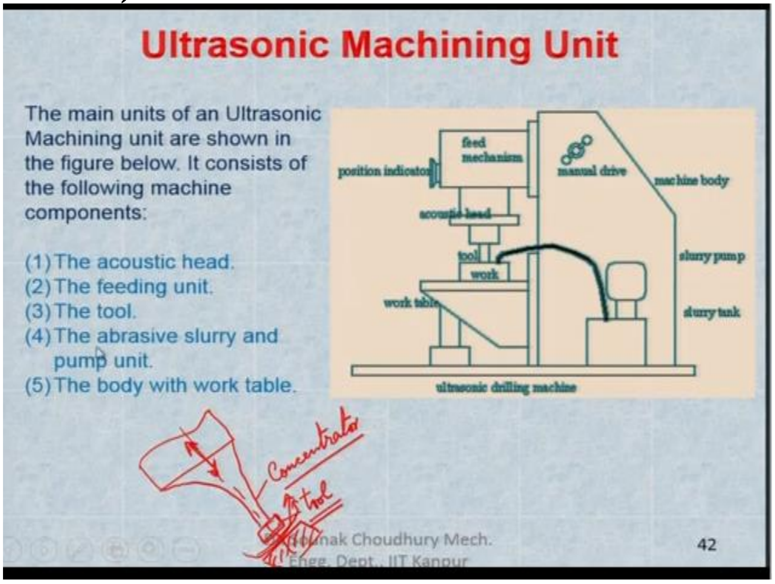

The ultrasonic machining unit is the following. This is the basic machine body, here we have the slurry pump and the slurry tank where it is supplied to the machining zone, where we have the work on the work table and the tool here which is mounted on the acoustic head and this is the tool, it is not to scale.

That particular shape is given to the acoustic head to concentrate the vibration. This is vibrating at a very high frequency and low amplitude and this is a concentrator. Therefore, it is called the concentrator. This is not shown here, this is simply said this is tool, but this is the concentrator and this is the tool.

The tool is mounted at the end of the concentrator and the workpiece is this is the workpiece between the workpiece and the tool there has to be a stand-off distance so this is also not shown here. And through the stand-off distance, the abrasive slurry is passed as shown in the diagram. The main units of an ultrasonic machine are shown here in the figure.

It consists of the following components. The acoustic head as I said, the feeding unit, the tool, the abrasive slurry and the pump unit and the body and the work table. This is here in the head there is a feed mechanism, because, the tool has to be forwarded towards the workpiece because the material is being removed and the distance between the tool and the workpiece is increasing.

There is a stand-off distance which has to be made constant which cannot be changed. To make that stand-off distance constant, the tool has to be forwarded towards the workpiece as the workpiece is removed on this machine. This is the position indicator that indicator will show you what is the tool and the workpiece material distance or the stand-off distance.

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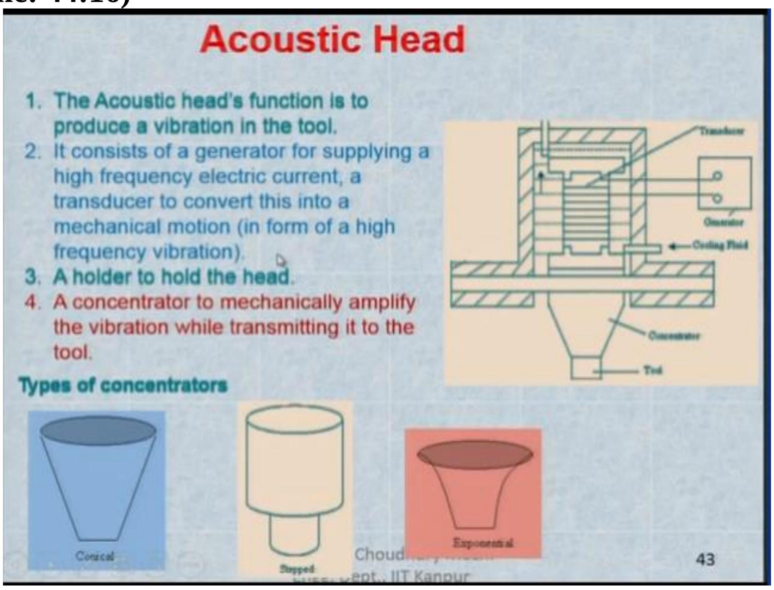

Acoustic head: these are the types of the concentrators shown here. This can be a conical which very popularly used. It can be a stepped concentrator or it can be an exponential concentrator, this is called the exponential concentrator, not the conical. Conical and the exponential shapes are more popularly used.

Here is the details of the acoustic head. This is the tool, this is the concentrator; here it is the conical concentrator. Since it is the high frequency here as I said that the frequency can be 20, 25 Kilo Hertz. At that high frequency the temperature produced will be very high. This is generated by means of a generator and this is the transformer this transformer helps in producing the required vibration that is required here. This is concentrated and it is important to the tool.

Since high temperature is produced, there will be a cooling fluid here this is to cool the surrounding of this concentrator and this is circulated this is the purpose of the cooling fluid. The function of this acoustic head is to produce a vibration in the tool. It consists of a generator for supplying a high frequency electric current through this a transducer to convert this into a mechanical motion in the form of high frequency vibration. A holder to hold the head; this is holder and it is inside.

Concentrator is required to mechanically amplify the vibration while transmitting to the tool. This is the concentrator, and these are the types of concentrators.

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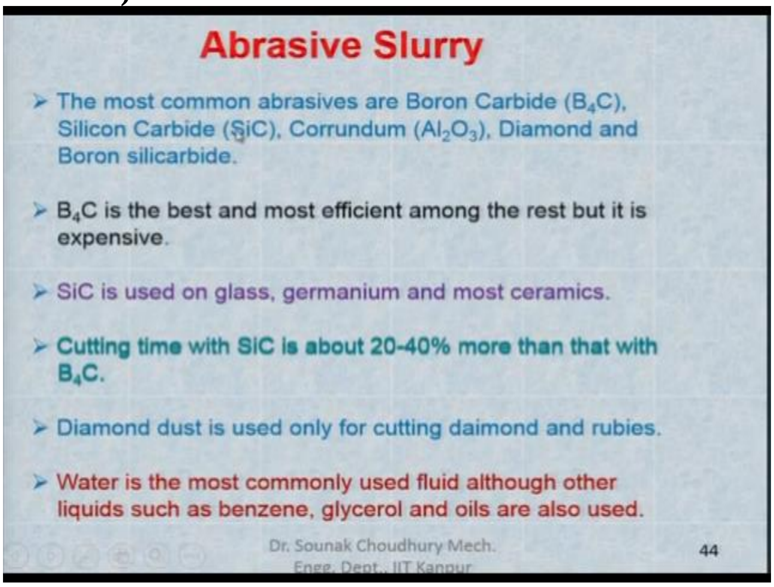

The abrasive slurry: the most common abrasives are the boron carbide, silicon carbide, corundum which is the aluminium oxide, diamond and the boron silicarbide. These are the more popularly used abrasives. B_4C is boron carbide which is the best and most efficient among the rest but it is more expensive. Now the silicon carbide is used on glass, germanium and most ceramics because the ceramics are brittle materials. Glass is also a brittle material and they are very hard materials. For that silicon carbide is quite suitable.

Cutting time with silicon carbide is about 20 to 40% more than that with the boron carbide. Now the diamond dust is used only for cutting diamond and the rubies that is the slurry that is used here. Diamond slurry is used in the form of a diamond dust but this you understand that it is expensive and so far being used exclusively for diamond, rubies where the high precision is required and the material is very hard and very brittle.

Water is the most commonly used fluid, although other fluids, other liquids such as benzene, glycerol and oils, these are also used. We mean to say that we mix the water or the benzene, glycerol, oil with these powders. Either it is a boron carbide powder or it is a silicon carbide powder or it is the diamond powder.

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Summary

Mechanics of material removal	Brittle fracture caused by impact of abreasive grains due to tool vibrating at high frequency
Medium	Slurry
Abrasives	B_4C, SiC, Al_2O_3, diamond 100-800 grit size
Vibration Frequency Amplitude	 15-30 kHz 25-100 μm
Tool Material MRR/Tool wear rate	 Soft steel 1.5 for WC workpiece, 100 for glass workpiece
Gap	25-40 μm
Critical parameters	Frequency, amplitude, tool material, grit size, abrasive material, feed force, slurry concentration, slurry viscosity
Materials application	Metals and alloys (particularly hard and brittle), semiconductors, nonmetals, e.g., glass and ceramics
Shape application	Round and irregular holes, impressions
Limitations	Very low MRR, tool wear, depth of holes and cavities small

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This is the summary. I am not going through this, I have already discussed this. This is tabulated.

This gap that is the stand-off distance, a critical parameter, we already said that material application is metals and alloys particularly, hard and brittle material, semiconductors, non-metals for example glass and ceramics. Shape application is the round and irregular holes impressions limitations they are very low material removal rate tool wear because it is a high frequency the abrasives and therefore the tool wears, so depth of holes and cavities is small because if you go to higher depth the energy is not sufficient. That means you have to increase the amplitude and the frequency.

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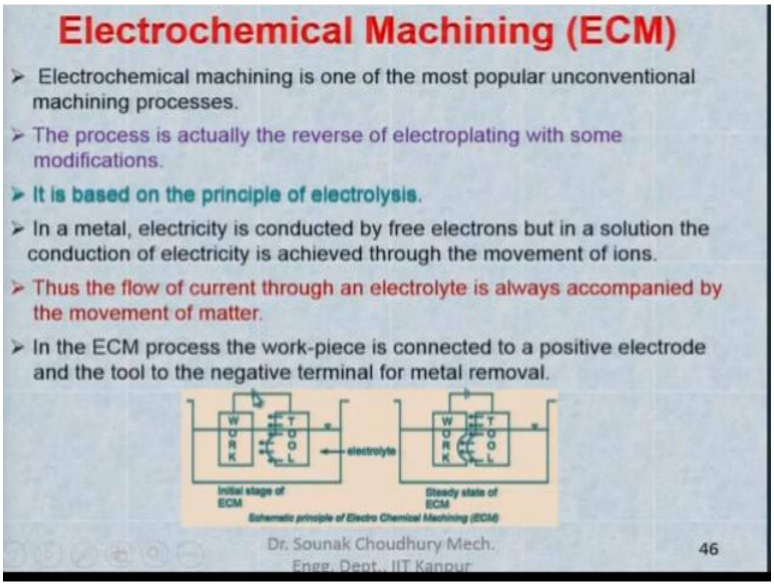

Next in line of the unconventional machining is the electrochemical machining which is one of the most popular unconventional machining processes. The process is the reverse of electroplating with some modification this I already mentioned in the beginning when I was discussing the introduction of the processes, it is based on the principle of electrolysis process we are all familiar with and the basis is the principle is of electrolysis.

In a metal, electricity is conducted by free electrons but in a solution the conduction of electricity is achieved through the movement of ions by solution we mean to say suppose some kind of an electrolyte there the movement of ions take place and the electricity is passed through this by the movement of ions. Thus, the flow of current through an electrolyte is always accompanied by the movement of matter.

In the matter means ions we are talking about in the electro chemical machining process the workpiece is connected to a positive electrode and the tool is to the negative. Let us say in this schematic diagram, we have the tool here the work here, tool has been made as the negative and the work has been made as a positive you can see from the diagram. Now here the tool is being advanced towards the workpiece and if the shape of the tool is like this, it is conformed on the workpiece surface.

The machining starts when the voltage is passed through the work and the tool through the electrolyte; both workpiece and the tool are dipped in the electrolyte and the machining starts when the stand-off distance between the tool and the workpiece has a certain value.

Because the distance is becoming more so the tool has to advance further. So, this is the schematic diagram of electro chemical machining. Once again, the workpiece you can see is connected to the positive terminal and the tool is connected to the negative terminal.

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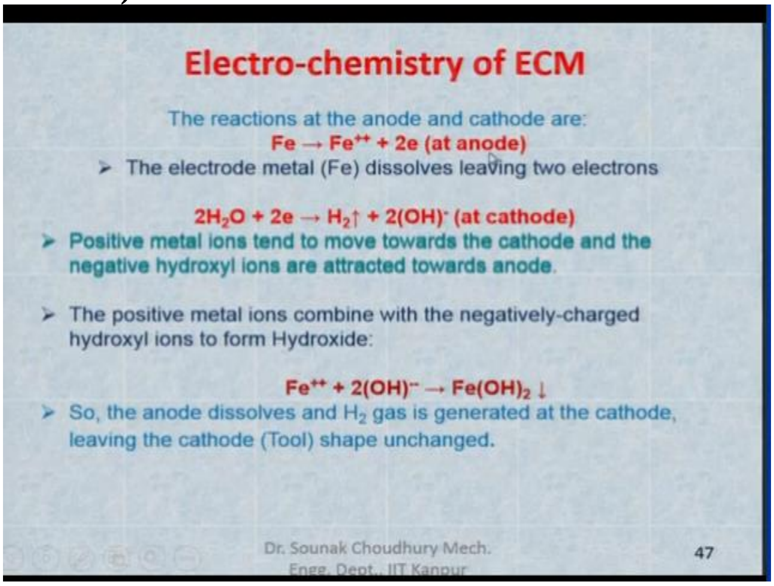

Now here is the electrochemistry of the electro chemical machining. Here is the anode. And this is the cathode, tool is cathode. Let us say this is the ferrous material. In that case, the ferrous in the anode will be like this that ferrous 2 ions will be created and 2 electrons will be created. Now the electrode metal ferrous dissolves because iron is created leaving 2 electrons that would be in the anode in the workpiece material.

The work is of the ferrous material and the tool is cathode. We want is to remove the material from the anode, from the workpiece. In the cathode, water plus this 2 electron taken from the anode which will create hydrogen gas and the 2 hydroxyl ion and the cathode.

The positive metal ions tend to move towards the cathode and the negative hydroxyl ions are attracted towards the anode. The positive metal ions combine with the hydroxyl the negatively charged hydroxyl ions and they will form the ferrous hydroxide, that ferrous hydroxide will precipitate. So, the anode dissolves in the form of the ferrous ions and finally, the ferrous hydroxide as you can see here. The tool, whatever is the material of the tool, nothing happens to the tool which is at the cathode.

So, ferrous is dissolved, but nothing happens to the tool because at the cathode, this is what happens that hydrogen gas is evolved from the electrolyte that we have it there where both tool and the workpiece are dipped. And ultimately the ferrous ions which are produced at the anode, it will be precipitated as the ferrous hydroxide. So, the anode dissolves, hydrogen gas is generated at the cathode leaving the cathode shape unchanged.

This is one of the biggest advantages of the electro chemical machining that here the tool does not wear out, nothing happens to the tool. We can use the tool for a very long time because there is almost or there is no wear of the tool. This is one of the advantages of the process.

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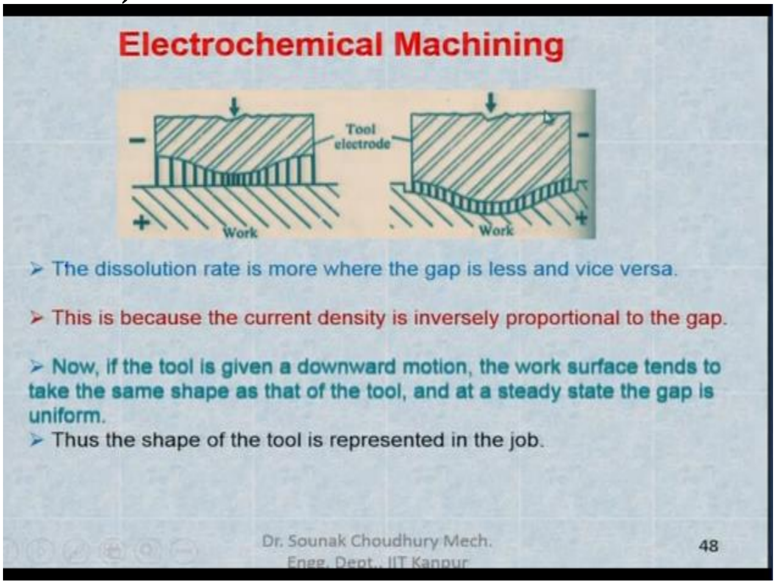

Here the electrochemical machining is schematically shown. This is the tool which is the cathode and workpieces is anode. The gap between the tool and the workpiece material when it is maintained at a proper level, which is the stand-off distance, then as you can see the workpiece is being removed. This much material is removed and the workpiece shape is becoming the same as the shape of the tool. That means the shape of the tool is conformed to the workpiece.

There should be a movement of the tool towards the workpiece because the stand-off distance is increasing. This is the schematic diagram of the electro chemical machining which is showing the principle of the process. I will once again repeat that electro chemical machining is one of the most popular processes where mechanism of the material removal is by electrochemical dissolution.

And as we have seen that in the electrochemical machining the workpiece is removed, material is removed from the workpiece and nothing happens to the tool material. If the tool material is even the soft material, it can be used for longer period because the tool does not wear out because at the cathode only the hydrogen gases evolve.

If you see this, this is the process wherethe ultimately the material is removed from the anode which is the workpiece and at the cathode, nothing happens but the hydrogen gase is evolved. Rest of the material in this topic of the electro chemical machining, I will discuss in the next session of discussion. Thank you for your attention.