Advanced Machining Processes

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Week - 02
Lecture - 04
Introduction: Numerical problems and USM unit

A quick recap of what we did in the last lecture. So, we actually tried to investigate the Shaw theory and tried to predict the material removal rate of a USM process ultrasonic machining process by using the Shaw's model. We also subsequently saw that there are 2 ways of removal of the material. One where you know it is the material removal is because of direct hammering action of the tool on the grains. And the second way of material removal is because of a reflected grain which comes off the surface of a tool and that is impacted or that impinges on to the workpiece and moves some material by flowing the material off. So, these are the 2 principle ways of doing USM and material removal subsequently.

And we also found out that the depth of indentation hw the amount of impact that you know the grain would have because of direct hammering is much more in comparison to the amount of impact that it would have otherwise. So, this is hw dash. So, hw is much greater than hw dash. And then we actually investigated some trends of material removals rates on various machining parameters like the amplitude of motion, the frequency of the vibrating tool head, the grain diameter, the average grain diameter so on so forth.

We also subsequently saw that there is a little difference between the theoretical model estimating the material removal rate of a USM process predicted by Shaw and the experimental in terms of grain diameter. And what experimental studies have suggested is that the material removal rate is proportional to the single power of the average grain diameter small d. Whereas, theoretically predicted model predicted the material removal to be proportional to d to the power of 3 by 4. And so we saw how Shaw very nicely studied a correlation between the projections on a grain surface and the overall diameter average diameter of grain. And by putting it into his theory he could actually balance the theory you know to the experimental data which had come.

And so we could have finally, the MRRQ proportional to the diameter d. So, in terms of non-conventional machining, some of these situations do happen where there is a force fitting of the experimental the theoretical model into the experimental world which comes into picture. But, they have high utility because the predictive theory actually gives you a framework through which at least some of the parameters machining parameters can be very closely investigated as to how they impact the material removal rate. And the whole purpose of any machining process whatsoever are 2-3 folds 1 is how or what the average roughness of a you know cut surface would be or what is the material removal rate or yield of the process is a very major aspect of all machining processes. So, is that for USM.

So, today we will actually do a numerical design of 1 such machining operation and try to estimate using Shaw's theory what is the material removal rate which would finally, come out. And for doing that let us look at this problem here. So, we want to find out the approximate value of time of machining needed for a square hole the dimensions of the holes are given to be 5 mm into 5 mm square. And it is actually in a tungsten carbide plate having a thickness of 4 mm thereby meaning that the volume is actually 100 millimetre cube. The abrasive grains are of diameter 100 microns or so, 0.01 mm and sorry 10 microns or so, 0.01 mm. And the feeding is done with a constant force of 3.5 Newton. So, the feed force of the average of the tool head is 3.5 Newton.

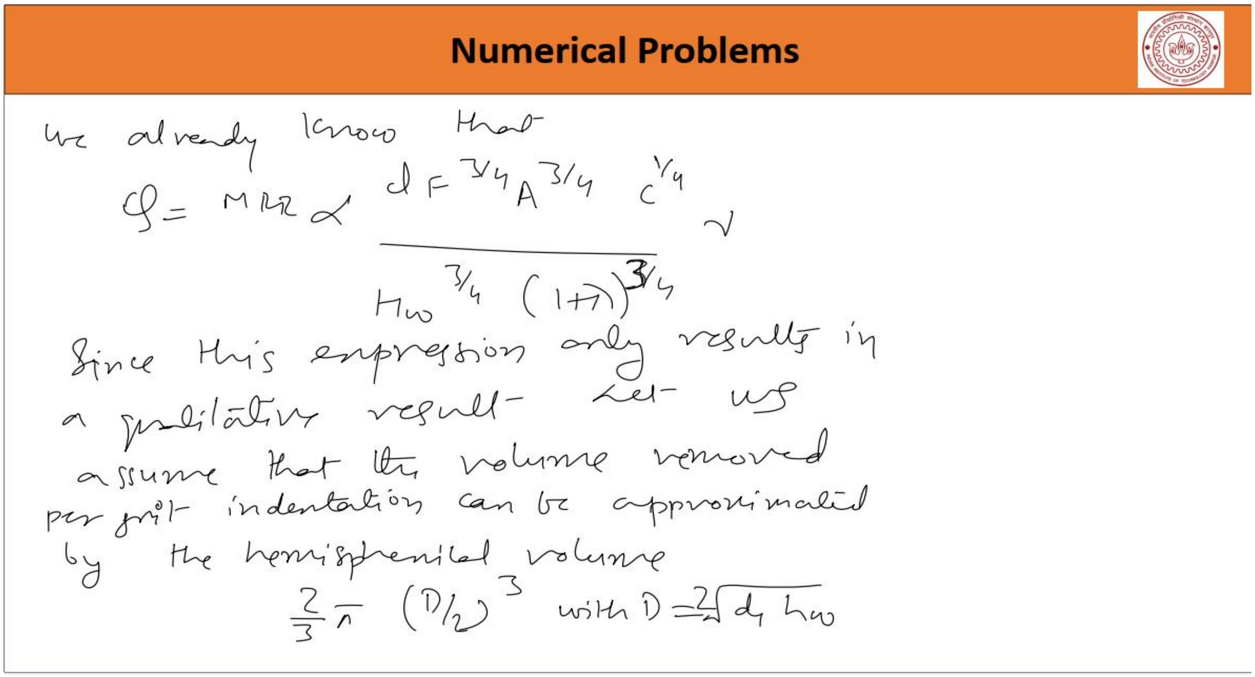
The amplitude of oscillation the tool oscillation is about 25 microns which is typically the distance between which the tools operate. The frequency of operation is very high it is about 25 kilo hertz the ultrasonic range. And some other parameters related to the metal are given here for example, the fracture hardness of the tungsten carbide sheet is approximately 6900 Newton per millimetre square which comes from the indentation test particularly assuming hemispherical indentation. So, it comes out to be 6900 Newton per millimetre square.

And the slurry contains 1 part of abrasive and 1 part of water meaning thereby that half the volume of the slurry is containing abrasive particles. And we assume that the coefficient in the you know Shaw anomaly is equal to 1 meaning thereby that the diameter of the projection is actually equal to the square of the average projected diameter of the grain. So, assuming this to happen let us now see what is the minimum time which is needed to you know machine this hole this square hole. And for common sense or intuitively one can see that the minimum time will only happen when the tool head is having the same dimension as the dimension of the hole which is machining. So, tool head should be about 5 mm into 5 mm in diameter.

So, that you know if it is any smaller than it would be in multiple passes of the tool thereby increasing the time. So, if it is at 1 go the tool head has to be of the same size as the size of the cavity or the hole that is 5 mm into 5 mm. And so, let us actually start doing this numerical problem. So, we already know from the Shaw theory that the material removal rate Q you know MRR is proportional to, and this is the modified Shaw theory. So, it is proportional to the single power of the grain diameter average grain diameter small d 3 by 4 of 3 by 4th power of the average force of the tool 3 by 4th of the amplitude that the tool undergoes is proportional to the 4th power of the concentration of the abrasive grains in the slurry proportional to the single power of the frequency of the vibrating tool head.

And also, is inversely proportional to the flow stress of the workpiece to the power 3 by 4 and 1 plus hardness ratios of the workpiece and tool to the power of 3 by 4. So, since this expression only results in a qualitative aspect of the machining process for sake of simplicity, we assume that the volume removal per grit indentation can be approximated by hemispherical volume. So, we assume that volume removed per indentation of the grain is approximated by the hemispherical volume 2 by 3 pi times of D by 2 cube where actually D is again related to twice root of d1 times of hw, d1 is the grain diameter or grain projection diameter, hw is indentation depth of the grain alright. So, that is what the MRR would really be. So, therefore, as we already know that we have a correlation between hw square depth of indentation, and these other different parameters force average times of amplitude divided by pi the grains in contact with the workpiece per impact times of d1 which is the projection diameter grain times of hw 1 plus lambda.

And we already know that F average is actually equal to 3.5 Newton's as illustrated in the numerical design problem as such the amplitude of motion A is given by 25 microns. So, it is basically 25 10 to the power of minus 3 millimetres and the frequency nu is given by 25 kilohertz. So, 25 10 to the power of 3 hertz. So, MRR in this case can be estimated by the total volume V which I already defined before as 2 by 3 pi D by 2 cube where D is equal to twice root d1 hw times of the number of particles making impact at 1 cycle or 1 impact of the tool times of nu the operating frequency of the vibrating tool head.



So, let us actually find out what would be the Z value to begin with. So, what is Z? So, as we already know that the numerical design allows 1 is to 1 ratio of the fluid to the abrasive particle meaning thereby that supposing if we have a tool head here which is actually same as that of the hole size is 5 mm into 5 mm just for minimum time for the sake of minimum time, I have very well explained this previously. So, the total area which is available of this tool is actually 25-millimetre square total area available and this area has to be flooded by you know a slurry between this and the workpiece surface which is situated down here. So, this whole volume has to be fitted by a slurry which essentially contains these particles in the ratio of 1 is to 1 meaning thereby the 50 percent of this area half of this area needs to be inundated with particles. And the particles as you know already are having an average grain diameter d with an area of pi by 4 or pi d by 2 square pi r square.

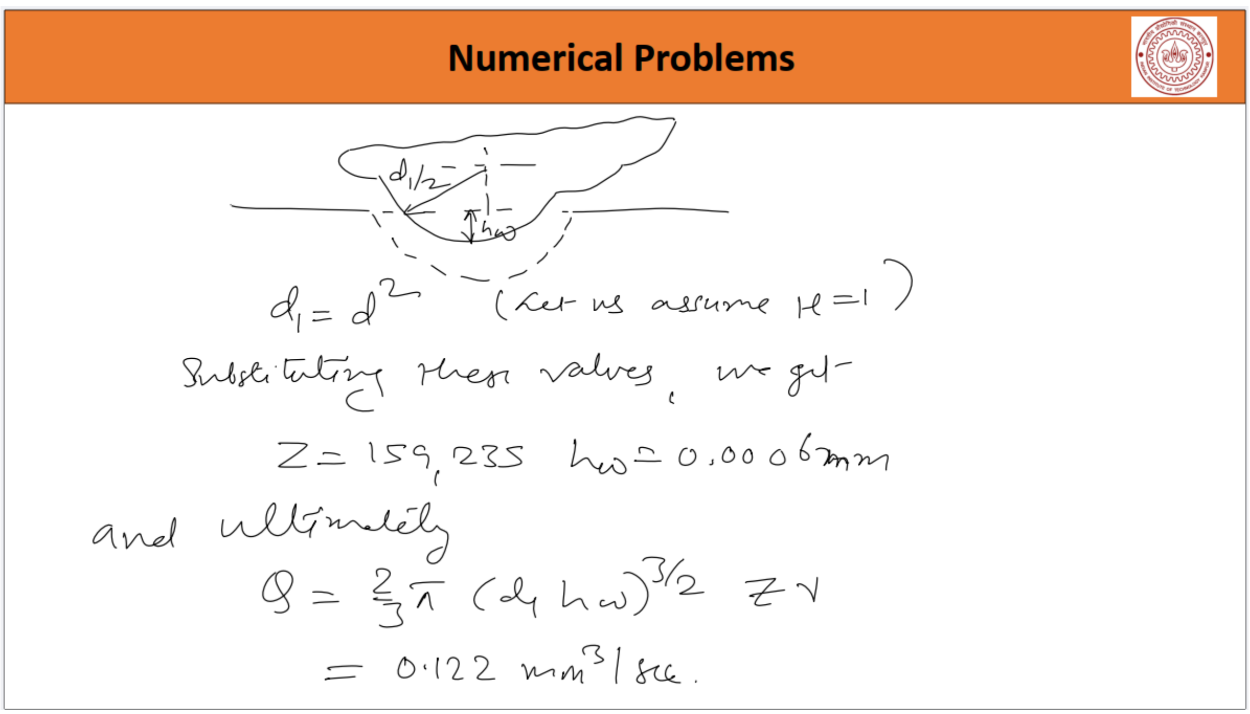
So, this is the area of projection of 1 grain. We have very well illustrated it before it is basically this area here right here of 1 particular grain. We assume all the grains to be of similar size by the Shaw's theory. So, these are all the diameters the average diameters of the whole grain. So, therefore, the numbers which are available per impact between the tool and the workpiece here would be given by the total area to be flooded with the particles by the individual particle projection area right.

And therefore, if we assume the grain diameter d as we had illustrated earlier to be about 25 about

10 microns about 0.01 mm. Then we should be having a ballpark figure of what this Z value could be. So, we assume hemispherical impact. And we know that for a spherical indentation test for hemispherical indentation.

So, this is also known as the Brinell's test. The hardness of the steel at 50 percent impregnation comes out to be 1360 Newton per millimetre square. The problem already defines that such a hardness if you consider in terms of the tungsten carbide. So, hardness of tungsten carbide that is the workpiece material for an identical 50 percent impregnation is given to be about 6900 Newton per millimetre square. So, obviously, the lambda value which is nothing but the hardness ratio between the workpiece and the tool as illustrated many times before comes out to be about 5 right 6900 by 1360.

So, it is about 5. So, we have the lambda value here, we also have kind of a ballpark figure for the Z value here. And the Z value you know if you consider the value of the diameter as 0.01 is actually coming out to be about 159235. So, so many particles are there between the this tool surface and the workpiece surface assuming a 1-to-1 ratio of the fluid to the abrasive particle in the slurry. So, we already have the Z value, we have calculated the or modeled the lambda value.



And now the question of the grain projection comes into picture. So, as you know here, we had already assumed that let us say, for example, this was the deformation of the grain surface had. So, the grains are represented by some projections of different diameters right. And this diameter here for example, of this particular sphere is d1 and the average grain diameter somewhere here is may be about small d. So, in this case, as I told in the previous Shaw theory the d1 is proportional or found to be proportional to square of d.

In this case as an equal to mu times of square of d, mu is 1 in this case and so therefore, d1 can be safely estimated as square of d. So, the d1 value comes out to be equal to square of the grain diameter and the diameter of the grain as you know is 0.01 millimetres. So, this comes out to be 10 to the power of minus 4 millimetre. So, this is actually you know it is just a correlation equation.

So, it is not dimensionally correct though, but then it is some kind of a correlation numerically between what happens between the let us say the value of d1 and the numerical value of the average diameter of the grain d without looking at the dimensional aspect of it. So, the grain diameter can be from experiments that Shaw did over a microscope predicted as about 10 to the power of this is the effective grain diameter 10 to the power of minus 4 millimetres of the surface. And while doing this there is an indentation hw that the grain would like to have on the surface here. So, this hw as you know has earlier been predicted by the equation 8 F average times of amplitude of motion of the tool head divided by pi Z d1 Hw times of 1 by lambda. We already know what d1 is from here we already know what the lambda value is it is about 5 which we calculated here.

The Z value earlier came out to be about 159235. So, even we know the Z value the average force has already been illustrated before as in the numerical problem to be 3.5 Newton's. So, this comes out to be 3.5 Newton's the amplitude of motion of the tool the oscillation of the tool is about 25 microns which means about 25 10 to the power of minus 3 mm.

So, putting all these values here the value of hw can be predicted as 0.0006 mm. So, that is about it the indentation depth. So, one thing that I would be very carefully looking at is that consider or think about the magnitude of the indentation that is happening on a surface.

So, it is only about close to 0.6 microns. So, even it is not even 1 micron. So, which means that the surface finish of such a process is expected to be very high. So, it is less than a micron finish about 600 nanometres up to which the indentation of single grain of size of about 10 microns can go for a magnitude of force which is as high as 3.5 Newton's with an operating frequency of 25 kilohertz of the tool head.

And you know and that too in a very hard surface of tungsten carbide. So, that is about the level of finish of such surfaces and therefore, from a conventional machining stand point these processes seem to have a better finish, better degree of finish of the surface the workpiece on which they are operating. Although their yield may be very small as I will just illustrate in the next you know set of calculations where we try to calculate the time that is needed for completely machining this square hole on the thick plate or about 4 mm thick plate of tungsten carbide. So, let us look at Q now. So, the value of Q is estimated as because it is a hemispherical indentation this 2 by 3 pi d1 hw to the power of 3 by 2 times of value of Z times of nu Z is basically the particles per impact and nu is the frequency.

And we if you plug in all the values for example, what this d1 would be we have already predicted what is this hw you know this about 0.0006 about 0.6 microns that we have again predicted the Z value is about 159235 nu, of course, is a very high frequency of 25 kilohertz. So, with all this on there, the amount of you know Q that you can calculate out is coming out to be about 0.122 millimetre cube per second.

So, this is not really a very high amount as is obvious from some of the conventional machining processes where you know it can be hundreds of millimetre cube of material coming per second. So, therefore, this process although on a comparative basis with the conventional process may not yield a very high material removal rate or yield, but does have a very high surface finish. And that is one of the reasons why for microsystems fabrication standpoint where material removal rate may not be the key component really, but what is do or does play a significant role is the surface finish. These processes are pretty important, and they can actually look at a domain of processes where an overall surface roughness which is acceptable to the microsystems engineering world can be achievable along with the reasonably ok material removal rate. Because some of the so-called MEMS processes which are conventional MEMS processes may take a huge amount of time generate a lot of waste for doing processing applications of some of these MEMS devices.

So, if you compare the non-conventional process in comparison to microsystem's conventional technology process, I would say that the non-conventional processes would be a high yield in the microsystems arena with a reasonable amount of surface finish that this processes impart. And so therefore, the flexibility of these processes or the way that this processes can be executed to build microsystems as such is higher in comparison to the conventional MEMS grade processes which are available mostly from the silicon industry or the polymer MEMS industry. So, let us actually look at how much time is needed for machining this hole. So, the square area so, the volume of the material that has to be removed as you know it is a 5 mm into 5 mm square hole with a 4 mm depth. So, it is 5 into 5 into 4 about 100 cubic millimetre and you know the amount of time that is needed.

So, the time needed for material removal becomes 100 divided by 0.122 which is about 13.66 minutes. So, a plate of about 4 mm thickness of tungsten carbide where an area of 25 square millimetre need to be removed on the plate would take about 13.66 minutes to get machined or removed.

So, it is really not a very high yield process in comparison to some other method like maybe drilling which exists in the conventional world, but the advantage here as I told you is that you can really focus very narrow using masking technology and you can also ensure that you have reasonable amount of surface finish or surface roughness in microns which can come or in a fraction of a microns which can come automatically by virtue of the nature of the process. So, that is how we have so if you look at really the actual time this is theoretically predicted time we should mind that that is a theoretically predicted time. If you look at really the actual time of the process, the actual time is much more than the theoretical time because we are assuming that this process is 100 percent efficient. That means, 1 impact is producing a flow, but that may not be the case because you think about it that if there are lot of abrasive particles packed in the slurry there is a possibility that there would be inter grain collisions there would be collisions with the debris as such which gets generated and there is a huge amount of chaos or randomness in the system of the particles the debris floating around in the slurry material. And therefore, the amount of you know material removal may not really proportionately be varying on the amount of grains which are impacting the surface.

Some of the grains for example, may have reduced momentum while they go close to the surface particularly in the free flow case and in the direct hammering case also there may be a case where there is a grain on grain because of which some complete crushing action may happen of 1 of the grains because of higher forces. So, all these sort of necessitate the process to be less than 100 percent efficient. So, if you look at the process typically it may take several more minutes about 30 minutes or 40 minutes for the whole process to get formulated which can be even up to the extent of 2 to 4 times of the predicted values and therefore, this is only an ideal case to give you a ballpark understanding of what could be time of removal of material for such a process. So, basically, let us look at a slightly different connotation now and let us see the impact of change of tool material on the machining time particularly in a USM process. So, let us say we have this example here where we want to determine the percentage change in the machining time for an USM operation cutting let us say a tungsten carbide plate.

When the tool material is changed from copper to stainless steel. So, intuitively one can really assume that what should change is the lambda value. Lambda as you know already is the hardness of the workpiece by hardness of the tool and the tool material is changing from copper to stainless steel S.S. So, therefore, because of the impact here, the overall lambda value should change. So, if supposing we had for the different tools Qs and Qc as the 2 MRRs for stainless steel and copper respectively.

So, we can easily write that Qc by Qs is actually equal to because nothing else varies it is only the lambda which is varying the workpiece remaining the same tungsten carbide. So, basically, the lambda varies typically between lambda c which is actually equal to H wc tungsten carbide by H copper to lambda S where lambda S is H tungsten carbide by hardness of S.S stainless steel. So, Qc by Qs comes out to be equal to 1 by lambda stainless steel S by 1 plus lambda copper c to the power of 3 by 4 for obvious reasons from the Shaw theory and the prediction and the approximation that has been discussed before where we find out that Qc is proportional to the inverse of 1 plus lambda power 3 by 4. So, therefore, supposing we consider these 2 aspects here lambda c and lambda s in both of the cases we can find out the you know both lambda c as well as lambda s are much higher in value than 1.

So, we can safely assume this 1 to be negligible here. So, 1 plus lambda c or 1 plus lambda s can be approximated by the lambda c and lambda s value. You already observed before that for a steel tool earlier this lambda for s was about 5 which is bigger in comparison to 1. So, you can easily safely neglect the 1 and make it equal to the ratio of both the lambdas. So, this can actually be represented as lambda s by lambda c to the power of 3 by 4 and that would eventually mean that the lambda s by lambda c is H copper or the hardness of the copper by hardness of the stainless steel to the power of 3 by 4. The hardness of tungsten carbide is same in both the cases as can be illustrated here.

So, we already know that the hardness of tungsten carbide to that of steel is about 1 3rd and therefore, Qc by Qs becomes equal to 1 3rd to the power of 3 by 4 and this is about 0.44. So, we can easily say that the time of machining when the tool is changed from copper to stainless steel is basically equal to the total volume that you want to machine using on the material removal rate of copper by the same volume by the material removal rate in case of steel is actually Qs by Qc and this actually is 1 by 0.44 about 2.27. So, you can say that the total time of machining is changed by a certain percentage. So, that percentage change in cutting time when the tool is changed from copper to stainless steel is tc minus ts by tc is a product with 100. So, it is 1 minus ts by tc this is 1 minus 0.44 times of 100.So, about 56 percent reduction. So, significant right.

Numerical Problems

Since, WC is much harder than both stainless steel & copper, η_s & η_c both are larger than unity.

$$\frac{q_c}{q_s} = \left(\frac{\eta_s}{\eta_c}\right)^{3/4} = \left(\frac{H_c}{H_s}\right)^{3/4}$$

$\frac{H_c}{H_s} = 1/3$, we get

$$\frac{q_c}{q_s} = 0.44 \qquad \frac{t_c}{t_s} = \frac{q_s}{q_c} = 2.27$$

So, therefore, just by changing the tool material between stainless steel I mean copper to the stainless steel you are actually reducing the machining time by 56 percent. So, as I already illustrated at the beginning of explaining ultrasonic machining the tool needs to be a little ductile in nature and the harder or the brittle the workpiece is the better it is in terms of material removal rate although the average roughness would go up. But the tool certainly needs to be ductile because the tool should be able to change its shape and retain its shape you know after every subsequent USM run. There is tool grinding of course, which is done sometimes and dressing which is done sometimes in a USM machine sometimes tool heads are also changed frequently from time to time for this aspect.

But then you can see that if it is a softer material of the tool then the indentation caused by the grain on the tool surface would be more in comparison to if the tool were harder material like S.S. So, when you have changed from copper to stainless steel the impact that the tool would have on the grain is more directly fed into the workpiece in terms of impregnation of the grain on the workpiece. And therefore, there is a huge amount of reduction in the machining time because S.S. is harder in comparison to copper. So, the selection of the tool material with respect to a certain grain is very-very critical to the successful operation of a ultrasonic machining process. So, let us now so, we have kind of looked at various design examples and what are the different aspects of the USM process.

Let us now focus a little bit on the ultrasonic machining unit how the machine would be or how the machine looks like and what can be modified or what appendages can be given to the machine for particularly microsystems fabrication process. So, let us actually see this unit here which is the USM unit it is a big machine and as you see there are several components of this machine there is a feed mechanism which ensures that the tool is fed at the ultrasonic frequency of very high about 20 to 25 kilohertz. There is a position indicator for closed-loop control where it gives you an indication of where exactly the tool is spaced at a function of time and it tells the feed mechanism whether it has to be moving towards the workpiece or away from the workpiece. There is an acoustic head which actually is the head which is responsible for creating the ultrasonic frequency. So, this feed mechanism is just feeding the tool and the acoustic head is basically the one which creates a frequency and typically as I will tell later this is realized by magneto strictive materials where there is a change in the dipole the magnetic dipole or the properties associated with the grains of the material with an ambient magnetic field.

So, if you keep on varying the magnetic field by a coil of current around that material it would change shapes and sizes and then it can actually vibrate at a very high ultrasonic frequency by an externally influenced magnetic field. So, the acoustic head is typically made of those magneto strictive materials. So, that is one part of it the acoustic head of course, the feeding unit which comprises of the feed mechanism and the position indicator. There is also a manual drive to the system. So, you can actually manually change the position of the tool with respect to the workpiece.

This right here is the tool head. So, that is what needs frequent replacements, and this is the tool really positioning itself with respect to the particles with respect to the workpiece. And the whole unit down here starting from the tool all the way to the bottom of the machine is made is because you have to be smoothly flow the abrasive slurry. So, you have a slurry tank here and there is a pump which pumps out the slurry from this tank and it sends it into this cavity here and the cavity is really where the workpiece is immersed. So, the work is actually immersed inside this cavity which already comprises of a flowing abrasive slurry. And so therefore, there is a continuous flow of the slurry into the work zone and taking away of the slurry thereby meaning that the debris which is generated is also carried away by the viscosity of the material which would have the abrasive particles into it.

And this worktable is a very heavy worktable where you can actually have a xyz position you know positioning or alignment mechanism for facing the different zones of the workpiece with respect to the tool. So, you have in principle the following units the acoustic head, the feeding unit, the tool, the abrasive slurry and pumping unit and the body with the worktable. So, that is all what goes into ultrasonic machining system. So, we look at individual components now this is what the acoustic head really is and the function as I have already indicated of the acoustic head is to produce a very high frequency vibration of the tool which would actually be in the ultrasonic range, and it would be able to machine a material based on that. So, it consists of a generator for supplying high-frequency electric current, a transducer to convert this into mechanical motion in form of high-frequency vibrations.

This right here is the generator, and this is the magneto strictive material the transducer which is actually having a coil. You can see this coils here coming from the waveform generator meaning thereby that if a high frequency is given to this coil then there is a change in the grains and so, there is always an external magnetic field. So, supposing there is a you know dipole moment set like this north south north south something like this and then there is an externally influencing magnetic field. So, this would change its shape on a certain you know the dipoles would rotate.

So, it can go to this direction also you know, and it can go back again. So, overall, the size of this material would keep on changing and vibrating on both sides. So, that is the case here. So, this whole thing is going up and down because of the change in the ambient magnetic field as done by the generator and that is what magneto strictive material does and there is a holder to hold the head of course. So, this whole you know system here is the holder and the holder has also some fluid which is a cooling fluid for particularly this current coil because it produces a lot of eddy currents and the magneto strictive material as such when there is a magnetic field and somehow it has to be also cooled simultaneously so that it goes to certain temperature. The there is a concentrator to mechanically amplify the vibrations while transmitting it to the tool.

The tool is kept at the end of this concentrator. So, this shape here is actually by design. So, whatever vibrations are emanating out of the magneto strictive material can be focused on to the tool very sharply. So, that you have less wobble in this direction and more vibrations in this direction and most of the transducers actually as I already told you you know works on this magneto strictive principle particularly because it is highly reliable in high frequency ranges 15 to 30 kilohertz is typically the operation frequency range of a USM tool and it also has low supply voltage and simple cooling arrangement which prevents the heating of this core the magneto strictive core of the particular transducer. And further, you know losses can be reduced by stampings as just as a way you use in transformers where there is some adhesive bonded between the various stamping so that currents may not be produced you know in the bulk it may be limited to these stampings as such. So, the dimensions are so chosen that the natural frequency sort of coincides with the electrical supply frequency and so you have everything done in resonance mode.

And so, all the vibrations which are generated by less amount of signal from the generator is first amplified using this or with first super concentrated using this concentrator and then also this whole system is on operating in resonance mode thereby meaning their amplitudes of motions would be very large for a small amount of vibrations. So, the full utilization of generator power can be made that way. So, that is how the acoustic head is made in a ultrasonic machining system. The other aspect of the system is how these you know concentrators work and as I already told you that the main purpose of the concentrator is to increase the amplitude to the level of to the level that is needed for cutting. So, you can see that for a small vibrations which are felt here the there is a sort of amplification in the amplitude as you go from one end of the concentrator to the other.

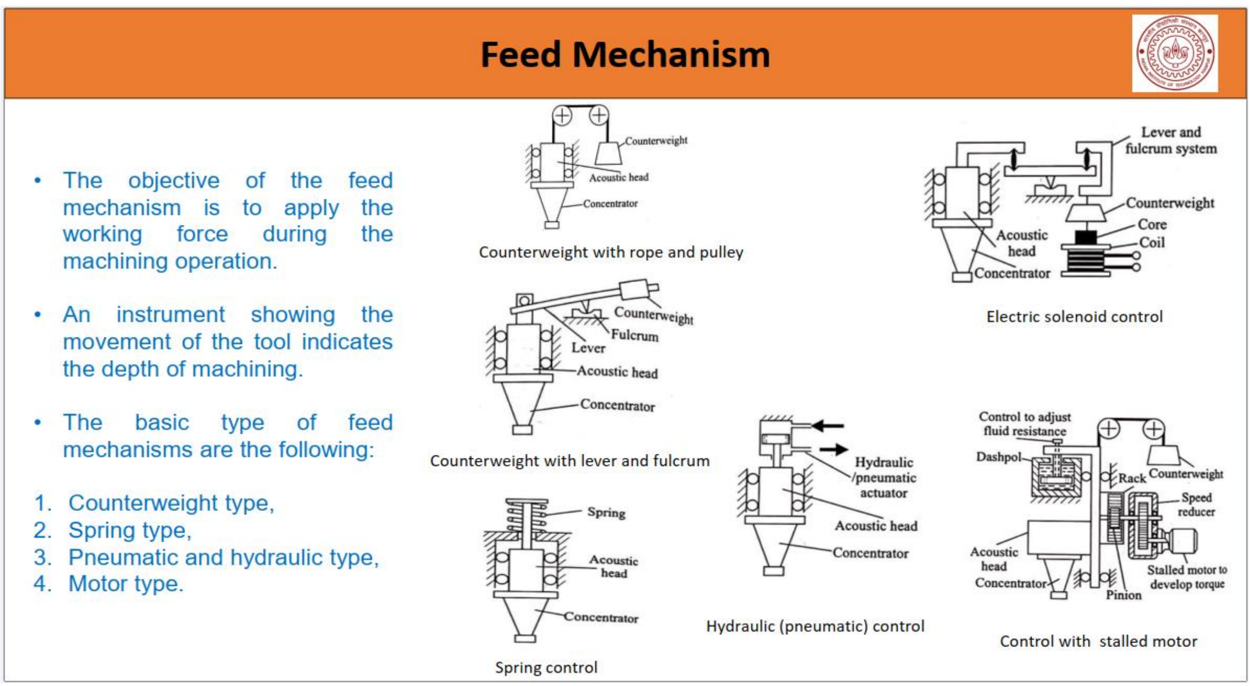
And this is also a plot which shows how the amplitude grows you know amplitude of motion grows from the end of the transducer to the end of the tip. And there can be various concentrators can be exponential conical or stepped form of concentrators which would do the same job as illustrated here in this particular figure. So, you can see the amplitude of longitudinal vibrations of the transducer concentrator assembly is amplified. And what is important is that the system should be held to the main body at a nodal point and that has to be very firm. So, that the transmission is 100 percent efficient between the transducer as such and the concentrator.

So, that is how the full details of acoustic heads are. The other important aspect is the feed mechanism of ultrasonic machines. So, as I already told you the feed mechanism is really not the mechanism which generates the frequency of motion. The frequency of cutting is generated by the acoustic head as I told before the feed mechanism is just to position suitably the acoustic head with respect holding the tool with respect to the workpiece. So, that you can actually utilize that frequency of the acoustic head very close to the workpiece surface.

So, that you can have maximum cutting action. So, the objective of the feed mechanism here is to apply the working force during the machining operation that is another objective. Because you are forcing the vibrating tool to get onto the abrasives. And there are various mechanisms for feeding. For example, these are some intelligent mechanisms which have been shown.

It can be counterweight with rope and pulley. There is a concentrator, there is a acoustic head, there is a counterweight. It can be a counterweight with lever and fulcrum. So, this is the lever and fulcrum arrangement. So, you can have a counterweight which is pulling this down and there is a force arm ratio with which you are actually trying to feed the concentrator. And then you have a electrical solenoid control here as you are seeing this again a lever with a fulcrum.

But then the force instead of giving through a weight you have a counterweight and a core coil which pulls or pushes depending on the signal which is available to the solenoid. Thus generating a motion to this end of the fulcrum and thereby increasing the feed and these are all guided. You can see this concentrated this acoustic head guided on a set of rails. So, as this motion is implemented this end of the fulcrum actually tries to push the concentrator towards the workpiece or away from the workpiece. You can have spring control the same thing can be done with the you know the k value of a static spring.



And spring can be the energy can be stored or released depending on the motion that you have to generate. And that in turns would actually feed the acoustic head close to the workpiece. You can have a hydraulic pneumatic arrangement as is illustrated here. There is a cylinder through which there is a piston which is moving up and down by pushing oil on both these chambers simultaneously, I mean you know alternately. So, that you can have up and down motion and that way we can actually feed the concentrator near close to the work surface.

Or you can have a positive feed mechanism using a stall motor which develops a torque through a set of gears. And that is the principle cause of motion and of course, you need a damper or a dashpot for you know absorbing some of the ramming effects of this feed mechanism. So, these are the different feed mechanisms counterweight type, spring type, pneumatic hydraulic, motor type so on so forth. And these are used very often in most of the USM systems ultrasonic machining systems. The other important aspect of a ultrasonic machine is the design consideration for the tool as such.

And the tool is as you know a very important component. I told you already the tool has to be of a strong, but ductile metal. You know most of the times it is found that stainless steel or low carbon steels you know act as a very good material for some of the tools. And if you compare them with some other softer materials like let us say aluminium or brass the tools made up of say soft materials where about sometimes 10 to 5 times more than the steel tools alone. And so, therefore, it is more important in certain applications where yield is more desirable to use a harder tool. But then sometimes you may have your process driven by the roughness requirement that you want to generate in the machining.

And there a softer tool may work out to be better because the indentation depth automatically reduces because of a change in the lambda value as has been illustrated in the Shaw theory. So, some of the geometrical features which are there on the tool are really decided by the process. For example, diameter of the circle that is circumscribed about the tool should not be more than about 1.2 to 2 times the diameter of the end of the concentrator and this actually indicates wobble.

So, supposing the tool is of diameter d this is the concentrator here the tool is of diameter d. And this actually executes a diameter meaning thereby the tool rotates from this position to this position like this. There is a wobbling action which is happening like this. So, the tool rotates like this. So, this diameter here of the rotation of this tool should not be 1.5 to 2 times you know should at least I mean it should be less than that 2 times the diameter of the end of the concentrator here.

So, that is how wobble is prevented. So, this is wobble tool wobble. So, these are some aspects that you need to be careful. The tool should be short and rigid because of obvious reasons that if you want to control this wobble the shorter the height of the concentrator from the acoustic head the better it is and the more rigid it is the less is the wobble. And typically, if you can one way of doing it is to make the tool hollow and when you make the tool hollow, hollow shafts of course, are more in rigidity in comparison to solid shafts. And therefore, the internal contour of such hollows should be parallel to the external one to ensure uniform wear and thickness of any wall or projection of this particular let us say concentrator should be at least 5 times the grain size.

So, that the abrasive does not go and indent and producing a hole on the concentrator. So, that should not happen. So, that is another aspect that the thickness of any wall or projection should be at least 5 times the grain size sufficiently thick for the grain to not indent and create a hole on to the concentrator. And in case of hollow tools, the wall should not be made thinner than about 500 to 800 microns because after that there is a tendency of the grains to automatically start you know playing around with the shell of the tool surface and some of the grains get reflected away and then they go into the concentrator. So, it is really not very wise idea for the concentrator material to be thinner than 500 or 800 microns. So, when designing the tool also the concentration should be given to site clearance which is normally of the order of about 0.06 to 0.36 millimetre, and this depends really on the grain size of the abrasive.

So, if the hole that you are about to so, let us say this is the tool and the hole that you are about to do is slightly higher here in the workpiece as you can see here. So, this is let us say the hole size. So, there should be some clearance given for the wobbling of the tool. So, that clearances of the order of about close to sometimes 60 microns or about 360 microns and it is highly dependent on what grain size you are using of the abrasive. So, see those some of the design considerations for the USM tool which is important and then the final aspect of USM system is the abrasive slurry.

And most of the common abrasives that are used are let us say boron carbide, silicon carbide, corundum, aluminium oxide, diamond boron silicarbide etcetera. So, boron carbide, of course, is the best and the most efficient among the rest although it is expensive you saw earlier that in comparison to a normal silicon carbide the boron carbide would have a higher you know material removal rate with respect to let us say concentration. And the average roughness of course, will be more so that there is more cutting action.

So, this is B4C and this is a SiC. So, this was how Q would vary with concentration. Now, one aspect is that when you are talking about glass or ceramics or germanium or some of the semiconducting materials, I told you that this process is widely used in microelectronics sometimes. You talk mostly about silicon carbide because it is sort of a soft abrasive compared to some of the higher hardness abrasives like boron carbide etcetera. So, the cutting time with silicon carbide sometimes is about 20 to 40 percent more than the boron carbide although what is important though is that the lower you know roughness average roughness would be realized using a silicon carbide material. So, if you talk about cutting diamond then of course, diamond dust is the only material which can be used particularly for cutting diamond or rubies or jewels.

And so, diamond dust, of course, is another kind of abrasive which can be used for the USM process. And when we talk about the fluid most of the suspensions are made in water. So, the slurry contains the water as the other part in abrasive or you know sometimes other liquids like benzene or glycerol, or oils are used which makes the viscosity slightly go up. So, there is at the cost of reduction of the material removal rate, but then slightly better dispersion occurs in terms of the abrasive materials. And sometimes in order to prevent coagulation between these materials you also use a surfactant which kind of prevents the coagulation by formulation of a charged monolayer on the surface of the abrasive.

So, all these aspects are there when we talk about preparation of the abrasive slurry. So, in a nutshell would like to summarize the mechanics of material removal for a USM process is really brittle fracture which is caused by impact of abrasive grains due to tool vibrating at high frequency. The medium of course, is the slurry which removes the material which contains dissolved abrasives it could be boron carbide, silicon carbide, aluminium oxide, diamond so on so forth. And the abrasive materials would have about 100 to 800 grit size which means maybe about 10 to 25 microns. The vibration frequency is about 15 to 13 kilohertz of the acoustic head and amplitude of motions realized therein is about 25 to 100 micrometers. Tool can be made up of a soft material like material like soft steel which is much better than other soft materials like aluminium or copper as we have seen before.

And the material removal rate to the tool wear rate particularly for let us say tungsten carbide work piece if you are using soft steel as a material and this is the lambda this is actually the ratios of the lambda. So, that comes out to be about 1.5 and if the material is brittle it goes as high as 100 which means that the brittle the material is the better it is for the both the AJM as well as the USM process AJM we have seen earlier. The gaps that are realized is about 25 to 30 microns between the tool and the workpiece. And some of the critical parameters of this process are, for example, frequency, amplitude, tool material, grit size, abrasive material, feed force, slurry concentration, viscosity so on so forth.

And tremendous amount of applications of these materials are particularly to the semiconductor industry and because MEMS is a fallout or microsystems is a fallout of the semiconductor industry. We do have a lot of implication of using mechanical energy application like processes like AJM or USM in the MEMS industry as such or microsystems industry as such. So, some of the limitations of this process are low MRR as I already illustrated it is a low-yield process high tool wear. And of course, the you have a limitation in terms of depth of cavity or you know the depth of holes that you can realize although in microsystems that is an advantage because the cavity that you are looking at actually is a close to some tens of microns in thickness.

And so, this process is very well used in microsystems for doing active fabrication. So, today we come to the end of this lecture, but then I would like to illustrate that in the next lecture I would give you a detailed overview of applications of both the AJM and the USM that is the mechanical you know mechanical energy-based processes non-conventional processes in fabrication of microsystems. Thank you.