Advanced Machining Processes
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Module - 01
Lecture - 02
Ultrasonic Machining Part 1

Welcome to the course on advanced machining processes. Today we are going to discuss on ultrasonic machining process. So this is the organization of my lecture okay.

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So first we shall discuss about that introduction of this ultrasonic machining then working principle of ultrasonic machining process then the elements or components of ultrasonic machining experimental sector and then parametric analysis whatever parameters are there then that effect of this parameter on the process performance we shall discuss and then process capabilities and the application of this process we shall discuss and then we shall discuss about the material removal model.

So there are different kinds of models are there for material removal okay. So we shall discuss that mathematical formulation of this ultrasonic machining process for material removal okay.

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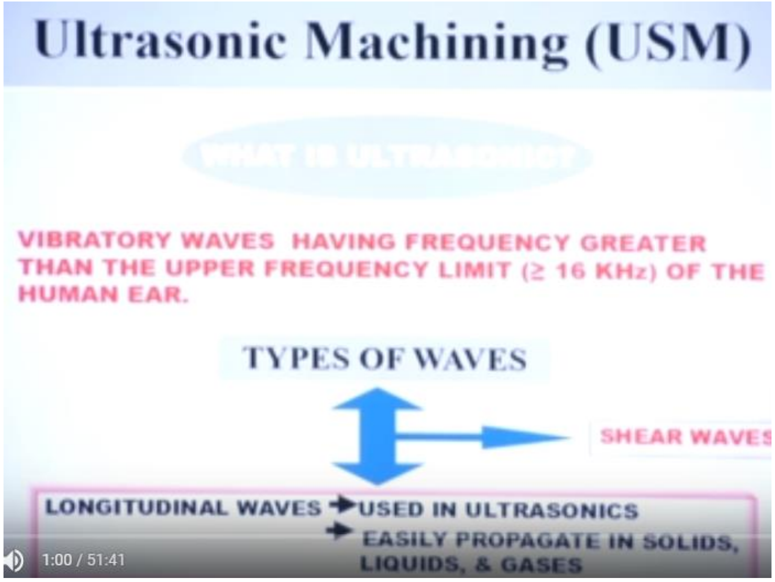

So first we shall we have to know what is ultrasonics okay. So when there is a vibrating waves having frequency greater than the upper frequency limit of human ear then it is called a ultrasonic frequency. So basically that limit of human ear is 16 kilohertz or 16000 hertz okay.

So when this frequency of this vibration is more than 16 kilohertz then we can call that vibration as ultrasonic frequency okay. So there are 2 types of frequency waves, there are 2 types of waves. One is longitudinal wave and another one is the shear wave.

So longitudinal wave we generally use longitudinal wave for machining purpose in case of ultrasonic machining process. So there are shear waves also there. So in case of ultrasonic machining process we generally neglect this shear wave okay. So longitudinal waves is used for ultrasonics and this kind of longitudinal wave is it can easily propagate in solids, liquids, and also in gases.

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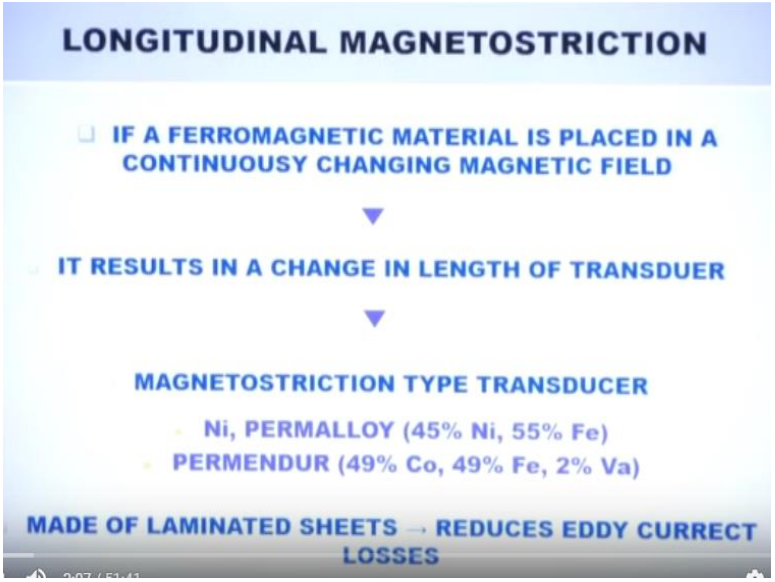

So what is longitudinal magnetostriction okay. So this magnetostriction or this kind of longitudinal wave can be generated by magnetostriction type transducer okay. So what is longitudinal magnetostriction. If a ferromagnetic material is placed in a continuously changing magnetic field so it results in a change in length of the transducer okay.

So suppose there is a change in magnetic field and you are putting one ferromagnetic material inside that continuously changing magnetic field, there is a change in length of that material okay. So as we are giving a very high frequency of this current okay so for changing that magnetic field so it will generate high frequency vibrating wave so longitudinal wave okay. So that high frequency wave we can use (()) (3:01) purposes okay.

So there are different kinds of materials which can give ferromagnetic materials which can generate this kind of or suitable for this magnetostriction type transducer. So one kind of material is nickel another one is the Permalloy. So because it is basically alloy okay it consists of 40% nickel, 55% iron okay. Another material is the Permendur which consists of 49% cobalt, 49% iron, and 2% vanadium okay. So this materials are made of laminated sheets.

Why we are using this laminated sheets because we are using AC current okay. So in case of AC current eddy currents are generated. So to reduce that process due to the eddy currents so this materials are actually made of laminated sheets okay. So what is ultrasonic transducer. Ultrasonic transducer it converts any kind of form of energy into the ultrasonic waves. So electrical energy it may be electrical energy okay so electric energy it is converted into the mechanical energy that is a high frequency vibration. So in case of magnetostriction type transducer that electrical energy is converted to the high frequency mechanical vibration okay.

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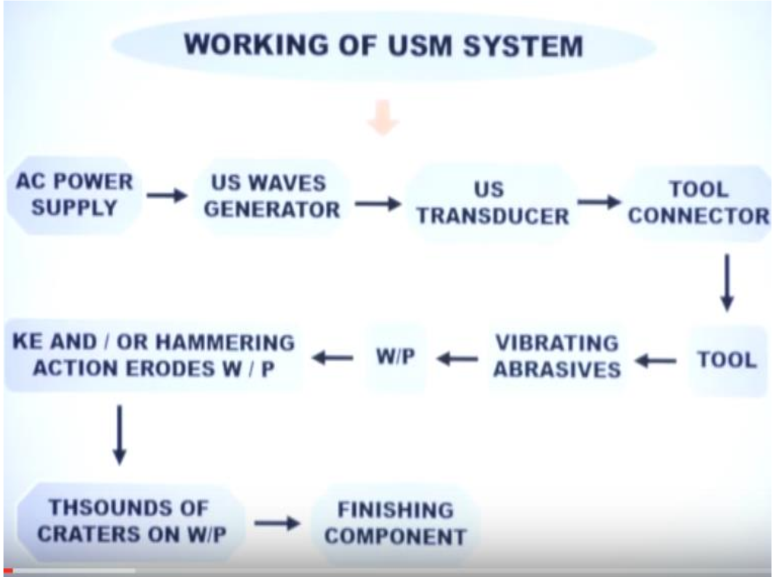

So what is the working of ultrasonic machining system. So there is a AC power supply which AC power supply okay so this AC power supply is connected to the ultrasonic waves generator.

So this ultrasonic wave generators it takes power from AC power supply then it is connected with ultrasonic transducer okay.

Then it is connected to a tool concentrator or tool horn and then tool concentrator is connected to a tool and then this tool is connected to a vibrating abrasives so just below the tool this abrasive particles are there inside the slurry okay and then this vibrating abrasives this abrasive particles hit the workpiece surface and because of this kinetic energy gained by this abrasive particles and due to the hammering action of this abrasive particles so there is a tiny chips are generated from the workpiece surface. So thousands of craters are found on the workpiece surface and we can get the replica of the tool to be produced.

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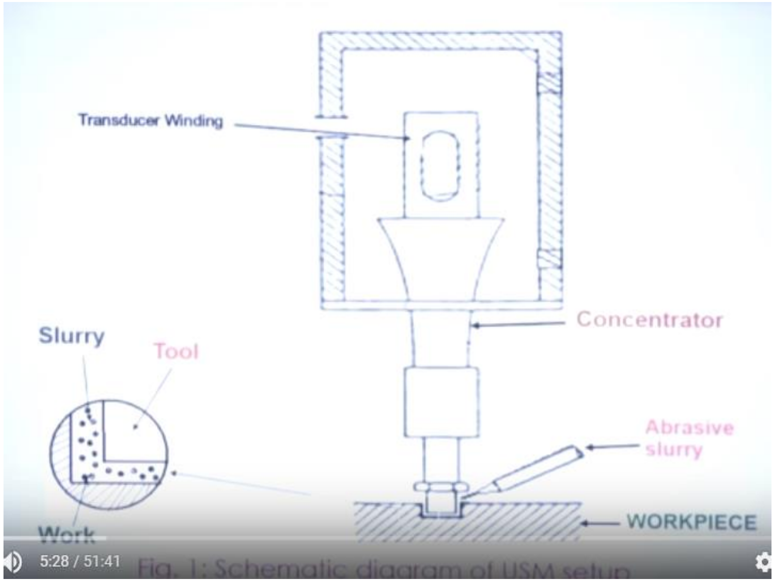

Now this is the schematic diagram of ultrasonic machining process okay. So now here you can see this is the transducer winding okay so here this is the transducer winding is there okay so inside there is a ferromagnetic material or ferromagnetic material is there okay. So moving on a high frequency current okay. So this high frequency current is generated in the ultrasonic waves generated.

So this ultrasonic waves generated this watt of this ultrasonic wave generated is that it takes current power supply from it takes the power supply and generate high frequency waves okay. So high frequency current it generates.okay. So this is the it these coils actually the high frequency currents are passing through these coils and because of this this ferromagnetic material there is a change in change in magnetic field in the ferromagnetic material and its length is changing okay.

So this coefficient of ultrasonic coefficient is E epsilon, epsilon is del l by l where del l is the change in length of the magnetostrictve material and length is L is the total length of that magnetostrictve material. So now this transducer, this transducer it is connected to a concentrator okay. So now this concentrator is connected to a tool holder and then this tool holder it is connected to a tool. So this is the tool here and this is the nozzle which is supplying the slurry in between this tool and this workpiece.

So this is the nozzle here, here we are using, it is shown cylindrical nozzle is shown here and in between this tool and workpiece this slurry is applied by this nozzle and this slurry consist of this water okay. Generally water is used as a slurry and this abrasive particles of different sizes abrasive particles are mixed with the slurry okay. So here this is the gap between this tool and the workpiece. So this gap is generated because the slurry it is provided by the nozzle here okay so through this nozzle slurry is provided and there should be a gap between the between the tool and workpiece for that slurry to come outside the watering zone or machine zone okay.

So this is the total experimental setup of the ultrasonic machining process. Here you can see this is the concentrator is used. Why this concentrator is used because whatever this transducer is generating this amplitude it is not sufficient enough to machine the workpiece surface. That is why it is connected to a concentrator so this working principle means working of this concentrator is that it amplifies the amplitude of vibration of whatever transducer is generating okay. So this concentrator has to be vibrated with a means this concentrator has to be vibrated with a natural frequency of the system okay.

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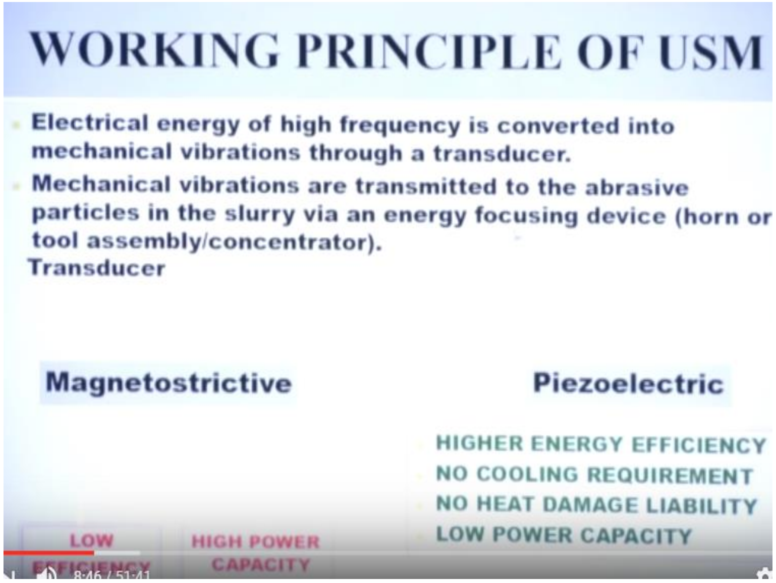

So now working principle of this ultrasonic machining process so there is the electrical energy of high frequency is converted into a mechanical vibration through a transducer. So till now we have discussed this magnetostrictive type transducer. So this mechanical vibration is transmitted to the abrasive particles in the slurry via energy focusing device or horn or concentrator or tool assembly and these abrasive particles just below the tool actually it gives the it gives the kinetic energy okay. So there is a this tool is vibrating with a very high frequency okay. So it is more than 16 kilohertz okay.

So now just below the tool there is a slurry is there. This slurry consist of abrasive particles. Because this transducer this tool is vibrating with a very high frequency these abrasive particles are just below the tool okay. So it is hit by this tool this abrasive particles is hit by the tool and this abrasive particles gain kinetic energy which is equal to the 1/2 mv square where m is the mass of this abrasive particles and v is the velocity of this abrasive particles okay.

So because of this kinetic energy is gained these abrasive particles after getting this kinetic energy it may hit another abrasive particle or it may directly hit the workpiece surface okay. So one more thing we want to say here this ultrasonic machining process it is suitable for very brittle and hard material, brittle and hard material.

So this when this abrasive particle hitting the workpiece surface this material is removed by the brittle fracture of the workpiece surface. So each each and every tiny abrasive particles which are hitting the workpiece surface is later is removed by the brittle fracture and tiny chips are actually generated from the workpiece surface very small tiny chips are generated from the workpiece surface.

Now you consider there is a tool it is a bigger diameter just below the tool so many abrasive particles are there and this tool is vibrating with a very high frequency so 16 amp 1000 kilohertz 16000 times per second. So how many how many attacks are there by the abrasive particle on the workpiece surface. So there are thousands of attacks per second by this abrasive particles.

Because of this kinetic energy of this abrasive particles it will hit and this tiny chips will be generated and after some time it will take the shape of the or tool okay. So this workpiece surface will take the shape of the tool. So this tool should be the replica of the workpiece to be made on the workpiece surface.

So any kind of complex geometrical shape can be generated or it may be it may generate through holes or it may go and generate blind holes. It may be cylindrical hole it may be square hole okay any kind of things can be done by this ultrasonic machining process okay. So it is very popular among the advanced machining process where this tool is the workpiece is very hard material and workpiece is very fragile material okay.

Suppose we are polishing we are machining glass or we are machining quartz. So okay so if we do this machining operation on a gliding operation or you can do this one this drilling operation in a drilling machine or in a drilling machine. So suppose this glass is there so glass immediately it will break if we use any drilling machine or milling machine or if you want to polish if we do on a gliding machine immediately there will be cracks will be generated okay. So because these are very fragile material and very brittle material.

So that is why we will need to have a very small forces. Now in this case as the abrasive particles are not touching, this tool is not touching through the workpiece surface directly okay so this energy is transmitted via this abrasive particles okay. So moment this tool is touching through the workpiece surface so this force coming through the individual abrasive particle is very less okay so that is why if this forces is very good for brittle material, fragile material, and very thin section of materials.

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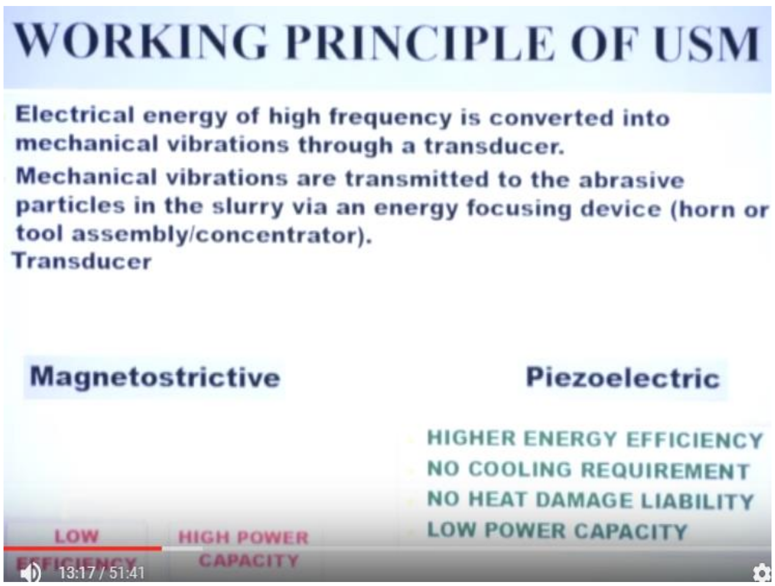

So there are 2 types of transducers are there okay. So now you understood what is transducer. This transducer is it converts any kind of energy into the mechanical energy. So in our case it is converting high frequency electrical energy okay so through this ultrasonic workpiece generated okay. So it is converting this electric energy high frequency electric energy into a mechanical vibration. There are 2 types of transducers are there. One is the magnetostrictive type another one is the piezoelectric transducer.

In both actually, both the systems generate high frequency vibration okay. So magnetostrictive we have already discussed, how it is generated. So in magnetostrictive type its efficiency is very less okay. So because most of the energy is utilized for the hitting okay. So so it generates lots of heat because its efficiency is low so rest of the things energy is means it is wasted because of hitting. So that is why we have to use some cooling system to release the heat from the transducer. So it has a low efficiency but it can generate high power capacity okay. So that is why when we need very high power capacity we can use these kind of magnetostrictive type transducer.

Another one is the piezoelectric type transducer so all we know. So its efficiency is very high. So that is why you do not need any cooling arrangement and that is why it does not have any heat that is liability but its power capacity is very less. So piezoelectric transducer (()) (15:03) so if you can if we pass a current through this piezoelectric material it expands and the reverse thing is that if we compress this piezoelectric material it generates current. So you are using the opposite thing okay so when some electrical energy is passing okay so this piezoelectric material will expand okay so this concept of this piezoelectric material is utilized for generating high frequency vibrator here okay.

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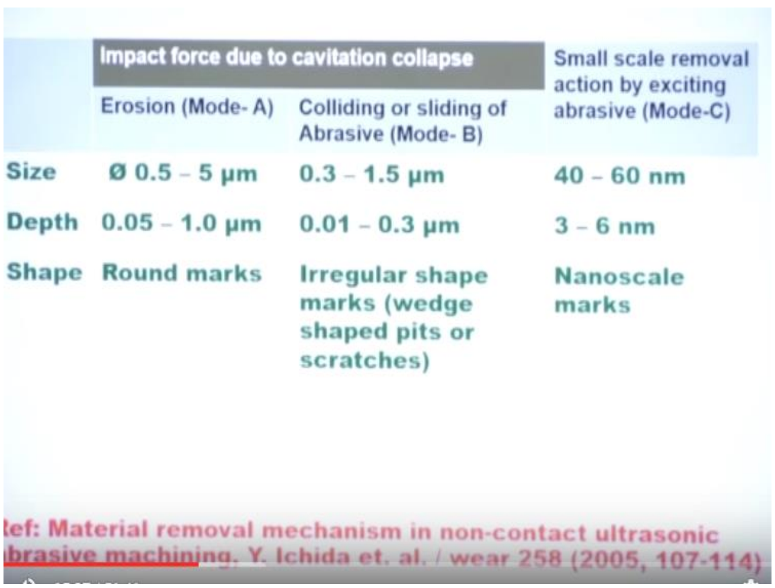

So there are different kinds of force or different kinds of models are there for material removal so first one is the erosion model which is called model A, second one is the colliding or sliding model sliding of abrasive model that is model B and third one is the small scale removal action by exciting abrasive okay so that is called model C.

So in model A erosion model the size or diameter of the craters which are generated it is 0.5 to 5 micron okay so it is quite high and for this colliding or sliding abrasive mode or model B mode B so the size of the crater generated is 0.3 to 1.5 micron and for the small scale removal action the size of the craters are generated, this is 40 to 60 nanometer which is very less and depth of the crater which is generated into the workpiece surface by each abrasive particle in case of erosion model it is 0.5 to 1 micron and in case of colliding or sliding of abrasive or mode B it is 0.01 to 0.3 micron and in case of small scale removal action okay so it is in mode C it is 3 to 6 nanometer.

So shape of shape of the geometry of the surface generated in case of mode A it is crater geometry of the craters generated which is in the round marks and for colliding or sliding or mode B it is irregular shape marks or wedge shaped pits or scratches and in case of mode C it is nanoscale marks. So this information is taken from this reference material removal mechanism in non-contract ultrasonic abrasive machining process by Y. Ichida et. al. which is published in wear that is an international journal.

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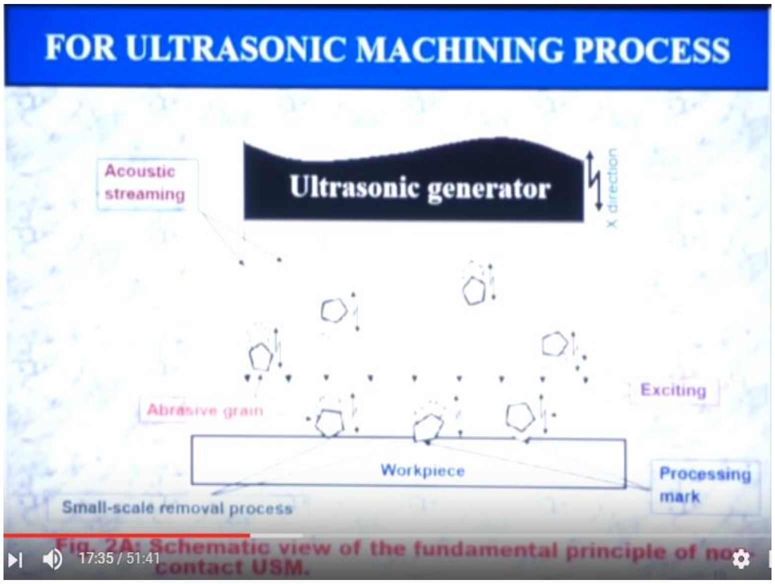

Okay so there are different modes are explained in this slide also in the next slide. So this one is the mode C or small scale removal of the process. So these are the abrasive particles which is hitting which is hitting due to the ultrasonic generator or which is tool which is vibrating with the ultrasonic vibration. So this is the detection longitudinal detection of this vibration. So this is the acoustic streaming of this wire along this longitudinal detection.

So because of hitting by this ultrasonic this tool these abrasive particles are coming towards the workpiece surface and it will make this tiny small chips on the workpiece surface. So these are the processing marks. So these are the exciting abrasive particles okay so small scale removal process is shown here.

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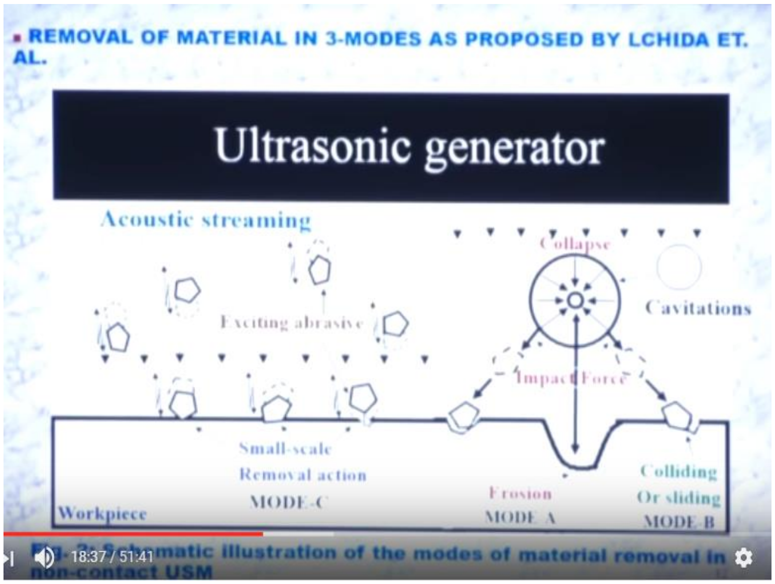

So in the next slide all the 3 modes, so in this slide all the 3 modes actually it is shown. So this is the fast mode here so which is in mode C here because of this exciting abrasive okay small scale removal action here almost spherical shape is generated on the workpiece surface. Now this is the mode mode B and mode A is shown here.

So this is shown this is due to the cavitation effect okay. So cavitation effect is there because it is vibrating this tool is vibrating with a very high frequency okay so there may be volume or pressure may be created just below the tool here. So here pressure may be created when these bubbles actually collapse okay so when these abrasive particles it moves with a very high velocity because of this collapse of these bubbles okay.

There are 2 modes are there so this is the one mode. This is colliding or sliding mode okay. So this is mode B and here this is the mode A this is the erosion mode by this cavitation effect. So now we have discussed there are 3 modes that is the small scale mode, colliding mode, and this is the erosion mode okay. So in this erosion mode you can see bigger size craters are generated and this colliding mode medium size craters are generated and in case of smaller scale removal mode C small scale removal is generated where craters are generated from the workpiece.

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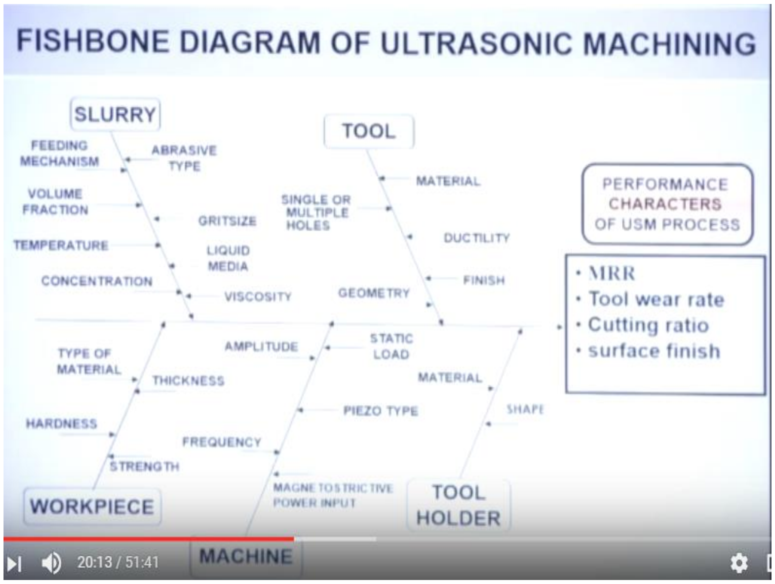

So now we have to discuss what are the different parameters of this ultrasonic machining process okay. So now we can think of this, this tool is the more most important parameter okay so this geometry of this tool should be the replica of this workpiece you want to generate on the workpiece surface okay. So tool is one of the main parameter, machining tool is one of the main parameter okay.

So now slurry is the another parameter okay. Now workpiece is another parameter. Machine is another parameter and tool holder is the another parameter. So these are the 5 parameters are there so each parameter it consist of several other parameters. So these are the 5 major parameters are there. So what is the performance characteristics of ultrasonic machining process. There are 4 performance characteristics or output of this ultrasonic machining process.

So one is the material removal rate okay. So at which rate material is removed from the workpiece surface okay. So this material removal rate are 2 types of material removal rate is there. One is the penetration rate that is in millimeter per second okay so that is the in downward detection at which rate this hole is generated and another one is the volumetric material removal rate. So how much volume of metal is removed from the workpiece surface so this unit is millimeter cube per second okay.

So the first output parameter is material removal rate. Second output parameter is the tool wear rate. So tool wear rate is expressed as tool wear rate means because this tool is also hitting the abrasive particles so there is a wear of this tool also there. So we want to minimize as less as possible because if we if high rate of wear of this tool whatever abrasive particles are there it may hit to another surface where we do not want any machining. So tool wear rate also one of the performance characteristics of this process.

So cutting ratio or ratio of material removed by the workpiece by ratio of material removal rate from the tool. So material removal rate by from by that workpiece divided by material removal rate by the tool will give the cutting ratio and surface finish obviously it is a very good it is a one of the main parameter okay. So high surface finish is expected for in means for any engineering applications of the components okay so now the slurry there were different sub parameters are there for this slurry.

So first one is the fitting mechanism. So how you are fitting this slurry into the workpiece tool and workpiece stand. So one thing we have shown that slurry can feed by slide okay through a nozzle we can we can we can provide slurry or we can make a hole into the tool itself okay. So so suppose the tool is suppose it is a cylindrical tool so we can make a hollow cylindrical tool and through this hollow here we can provide the slurry into the tool and workpiece okay.

Now volume fraction of the slurry okay so this is another parameter. Temperature of the slurry is also another parameter. So temperature actually because of this temperature this viscosity of the slurry also changes so that is why if viscosity changes then it means its property slurry property changes. So temperature has to be maintained within a certain range okay for getting efficient machine. So concentration of this slurry that is also another parameter and this slurry consists of abrasive particles also.

So this abrasive particles type is also an important parameter or rather the different types of abrasive particles we are using. One is the grid size of this abrasive particles and what is the liquid media or base media we are using for this slurry and also viscosity of this media or slurry is also an important parameter.

Now tool, what are the different parameters for this tool? This tool material is an important parameter. Then the activity of this tool material is an important parameter. So these tools are tool materials will be ductile okay so because there is a machining is going on because of this brittle fracture on the workpiece surface so it will take much more time for fracturing of the tool so if it is made of this ductile material and also finish of the tool also is very important thing. So surfacing is also is important in case of this tool okay.

Geometry of this tool also very important okay. So we can we can do the (()) (25:27) operation also suppose a bulk material is has to be removed. So we can use instead of a solid tool we can use a hollow cylindrical tool also okay. So if we use these kind of hollow cylindrical tool and if it vibrates so this circumference and area will be machined and total volume can be removed okay. So we are not including the total volume, we are removing the circumferentially this hollow portion okay. In that hollow portion we are not doing machining where these materials are there on the tool okay so in that portion we are doing the machining operation.

So another parameter is the workpiece So type of material of this workpiece, hardness of this workpiece, strength of this workpiece, and thickness of this workpiece, so these things are actually matters. Harder material it will take much more time okay for machining although this ultrasonic machining process also a very slow process but if we if we machine very hard material then it will take more time.

Machine so machine parameters are amplitude, amplitude of vibration, at what vibration it is vibrating and this frequency of this vibration how many sec how many vibrations are there per second that matters very much and piezo type what kind of piezo we are using. Also there is a static mode is there 2 static mode okay. Also there is a static mode is there and magnetostrictive power input what magnetostrictive power we are using okay and tool holder. What is the material of this tool holder, what is the shape of this tool holder okay that thing also matter okay.

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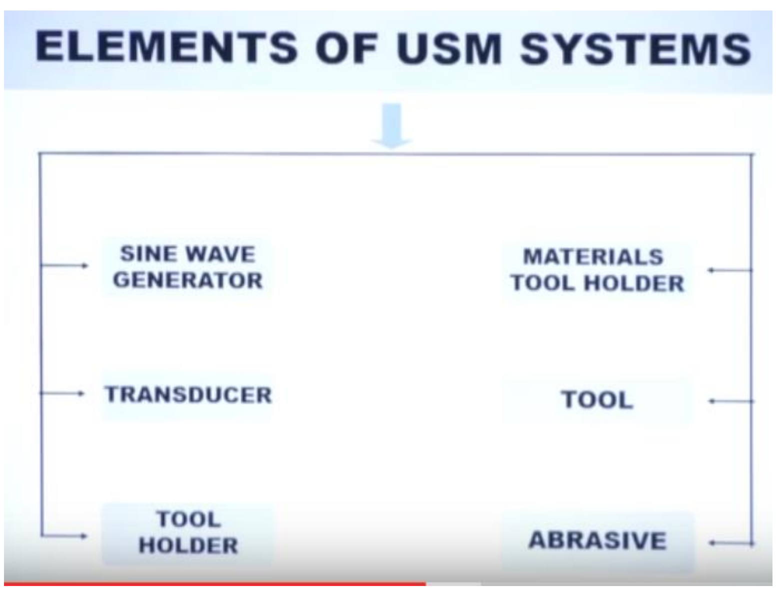

So what are the elements of this ultrasonic machining experimental setup. So first one is the sine wave generator, second one is the transducer, third one is the tool holder, fourth one is the materials of this tool holder, and fifth one is the tool, and sixth one is the abrasives. So these are the 6 components of this ultrasonic machining experimental setup okay.

So we shall discuss one by one, each of the components of this ultrasonic machining system okay. So sine wave generator it converts our line frequency is 60 Hz, 50 to 60 Hz, it converts low frequency or normal line frequency of this current with a high frequency current.

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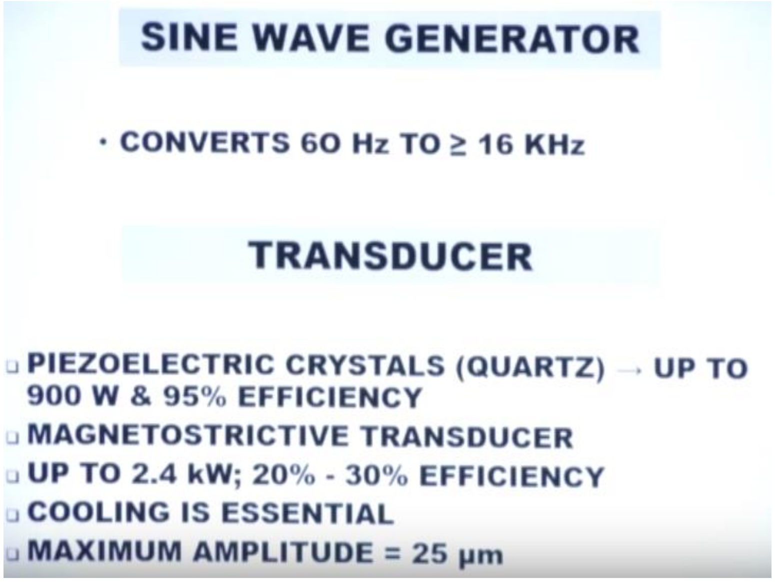

So high frequency it is more than 16 kilohertz. So the sine wave generators it converts this 60 Hz frequency of current to high frequency current okay. So now this high frequency current is fed to the transducer okay. So piezoelectric crystals are there or quartz. So its 2 types of transducer already we have discussed.

So if we consider this piezoelectric transducer so suppose this is materials are quartz so it can generate up to 900 watt and its efficiency is 95% and there are another kind of transducer we have discussed that is magnetostrictive type transducer. It generate 2.5 kilowatt and its efficiency is 20 to 30%, it is very low. So we need cooling system okay. So maximum amplitude of vibration is 25 micron in case of magnetostrictive type transducer. Now second one is the tool holder.

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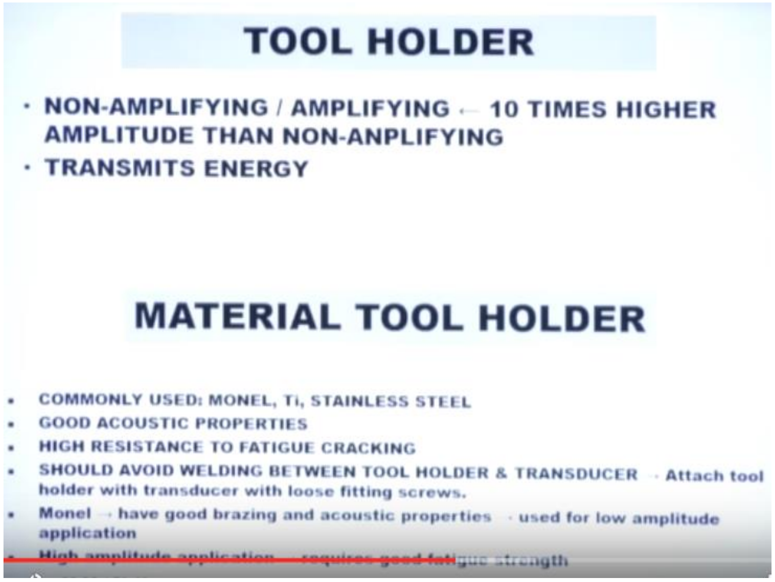

So tool holder I told that there is a concentrator is there okay. So this concentrator it is used to amplify the amplitude of vibration from the transducer because whatever transducer it is generating it is very less okay. So that is why it should be connected to a concentrator okay. So suppose we do not need any concentrator in that case we can use a cylindrical concentrator okay.

Otherwise, we can if we want to get this amplification of this amplitude of vibration in that case different kinds of metals are there okay. So different shapes are actually basically used okay for this concentrator. So tool holder it may be amplifying type or non-amplifying type. So in case of amplifying, so its amplitude it multiplies 10 times.

So if tool holder actually it transmits the energy. So what are the different materials for the tool holder? Commonly used tool holder materials are monel, titanium, stainless steel. So these are the materials used for this tool holder. It has a very good acoustic properties, high resistance to fatigue because this transducer this concentrator it is supposed to a it is in a environment of with a very high frequency vibrations are there.

So it can generate fatigue cracking. So to resist that fatigue cracking so this materials would have resistance to the fatigue cracking okay and that this tool holder should avoid holding between the tool holder and transducer. So as it is vibrating on the very high frequency there is chances that this transducer will stick together or join together with the concentrator okay. So attach tool holder and with the transducer with a loose fitting screws so that is the one mechanism okay.

So monel is the very good material for this transducer okay. So have a high wedging and acoustic properties and used for low amplitude application. So for high amplitude application we need to have resistance for good fatigue strength or you should have very good fatigue strength.

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So tool material it should be very soft material okay. So generally mild steel, stainless steel, brass these are the ductile materials are used for this tool material. So it should have high wear resistance. So surface condition for this tools should be good surface finish and there should not be any scratches or scratch marks or machine marks on the tool because if there is some scratches is there abrasive particle will get hit by this scratches and instead of vertically hitting to the workpiece it will hit or hit to some other places where we really we do not need any machining. We do not want any machining okay.

So that is why this also if there is a scratch marks are there these scratch marks also can generate fatigue cracking there. It can generate cracks may be generated from the scratch marks okay. So tool design consideration are we have to consider for the work cart. So work cart is actually we cannot avoid the work cart okay. So work cart is because of this when tool is doing means when you are doing the when we are doing the machining operation then tool is fit towards the downward direction.

So there is a tool fitting system is there because every time we have to maintain the proper gap between the tool and the workpiece surface okay. So to maintain that we have to fit the tool towards the workpiece okay. So when it is fit towards the workpiece sufficiently enough to the bottom okay. So in that case what happens that the sidewall from the sidewall of this tool also the abrasive particles are hit and it will it will cut it will do the hitting operation to the workpiece surface and it will generate it will it will generate craters from the sidewalls also or we can say that from the sidewalls also there is a because of this transfers detection this waves also do the machining operation okay. So there is a side cutting is there.

So we have to reduce that side cutting as much as possible. So we have to consider this so that and minimize we have to minimize the fatigue problem by silver brazing of this tool and tool holder by silver bracing of this tool and tool holder we can reduce the fatigue cracking.

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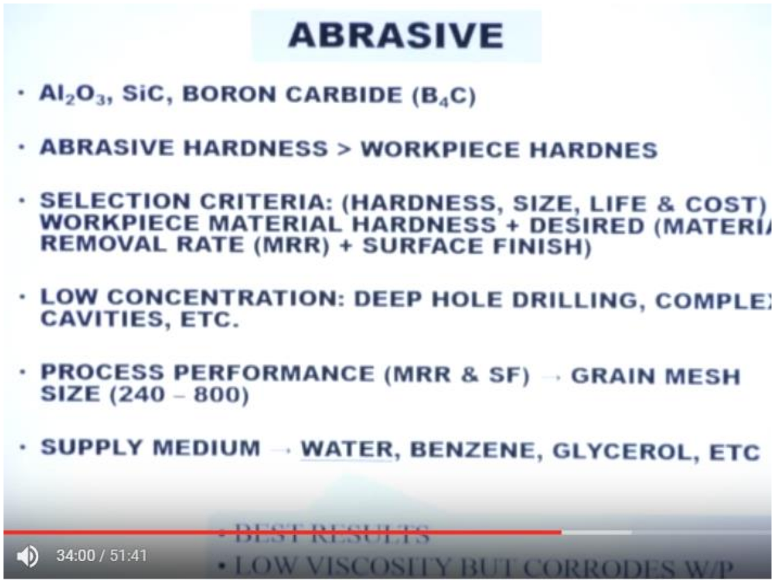

So abrasives different kinds of abrasives we can use. So here it is shown in in the it is sorted with with a means from lower hardness to the higher hardness okay. So aluminum oxide this is the so its hardness is lesser than other abrasive particles then means silicon carbide has high hardness than aluminum oxide. Then boron carbide it is more harder than the silicon carbide okay so in in case of increasing hardness it is shown here okay.

So obviously this abrasive particle hardness would be higher than the workpiece material hardness. Then only it can hit the workpiece and there will be brittle fracture. Otherwise, if hardness of this abrasive particles are lesser than the workpiece material then it will not generate any crack from the workpiece surface. So selection criteria, what should be the selection criteria, which abrasive particles because we have so many options are there so many abrasive particles are available in the market so which abrasive particles we should use. So it based on the hardness, size, and life, and cost of the workpiece material okay and so we have to consider the what is the hardness of this what is the hardness of this abrasive, size of this abrasive, life of the abrasive, and cost of this abrasive we have to consider. Then workpiece material hardness also we have to consider.

Suppose if it is very hard material like titanium then we have to use this boron carbide and desired material removal also important so material we want material removal rate as high as possible but at the same time we want very good surface finish okay. So if we want the material removal rate very high in that case we have to consider harder abrasive particles okay. So desired material removal rate and surface finish of the workpiece material also governs the which abrasive particle we should choose.

Low concentration of abrasive particles are used for deep hole drilling when length to diameter ratio of the hole so what is the length and what is the diameter of this hole is very high so L by D ratio so it is called high expect ratio of hole where this L by D ratio is very high so in that case we have to use low concentration of this slurry low concentration of abrasive particles in the slurry so that these abrasive particles would reach each and everywhere into the tool and workpiece that gap it should be uniformly distributed okay.

So process performance, better removal rate, and surface finish okay. Grain size generally it is 240 - 800 micron. Supply medium, water should be the base medium for this slurry, water is the best medium is used okay because of its low viscosity it can pass through means in between the gap between the tool and workpiece okay. So other options for this base medium is benzene, glycerol, and etc., okay. So now we have to do the parametric analysis okay. What are the effect of individual parameter okay what about the what is the effect of individual parameter that we have to do so that is why we need to do this parametric analysis okay.

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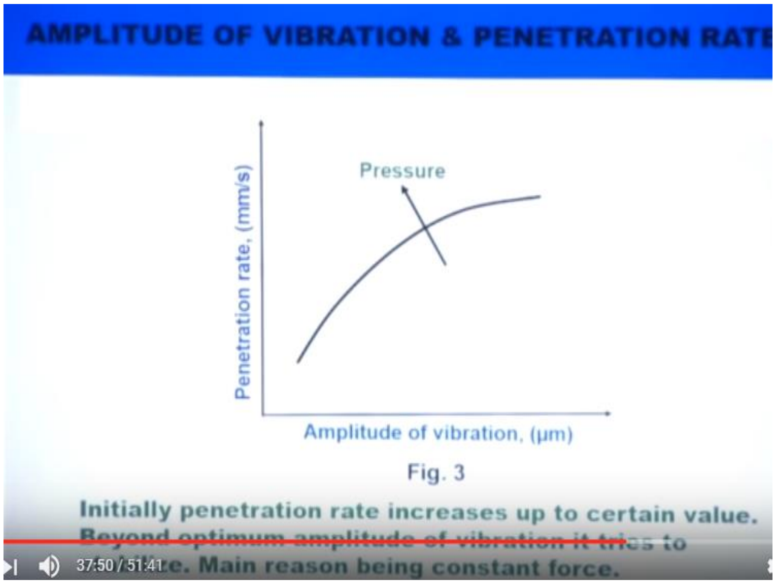

So main machine parameters are amplitude of vibration and frequency of vibration okay. So amplitude of vibration and frequency of vibration are the main machine parameter. So we can control from the machine this amplitude of vibration and frequency of vibration okay. So this is the plot have been between this penetration rate it is millimeter per second or we can say this is the minimum material removal rate okay and with the amplitude of vibration.

Now we can see if we it is the amplitude of vibration okay so in that case what happens these abrasive particle will get higher energy or higher kinetic energy because of higher velocity okay. So if we increase the amplitude of vibration your material removal rate will increase but after some time if you see after it reach the optimum value okay it stabilizes okay.

So it stabilizes after reaching to a certain value. So if we increase the pressure or load then also your penetration rate also increases okay with a with the amplitude of vibration okay. So initially penetration rate increases up to a certain value even the optimal amplitude of vibration it tries to stabilize (()) (39:06) in the constant force. So if we increase the amplitude of vibration what whatever static load we are using that is fixed so that is why whatever static load is using that is fixed so that is why okay. So if we increase the amplitude of vibration still after some time after optimum amplitude of vibration is achieved so there is a stall or it will stabilize.

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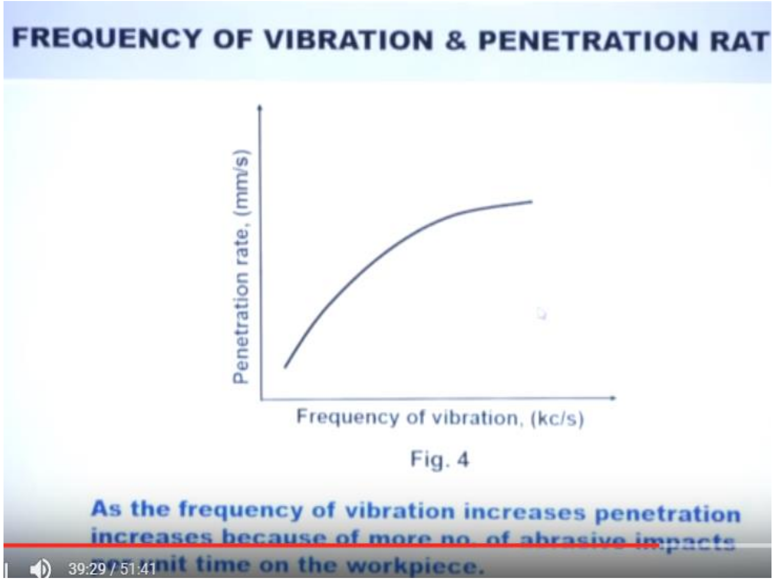

So now frequency of vibration, if we increase the frequency of vibration you can see okay so penetration rate or linear material removal increases. Frequency of vibration, if we increase the frequency of vibration then per second number of hitting by these abrasive particles increases. So more number of abrasive particles per unit time are hitting because this tool is vibrating with a very high frequency. So more number of particles are taking part into the machining operation. So more craters are generated.

So then this means this penetration rate increases but after some time you see this penetration rate stabilizes. So as the frequency of vibration increases penetration rate increases because of the more number of abrasive particles per unit time on the workpiece surface. But after it reaches the optimum frequency then you can see that it stabilizes okay. It stops when it reaches the optimum frequency and vibration.

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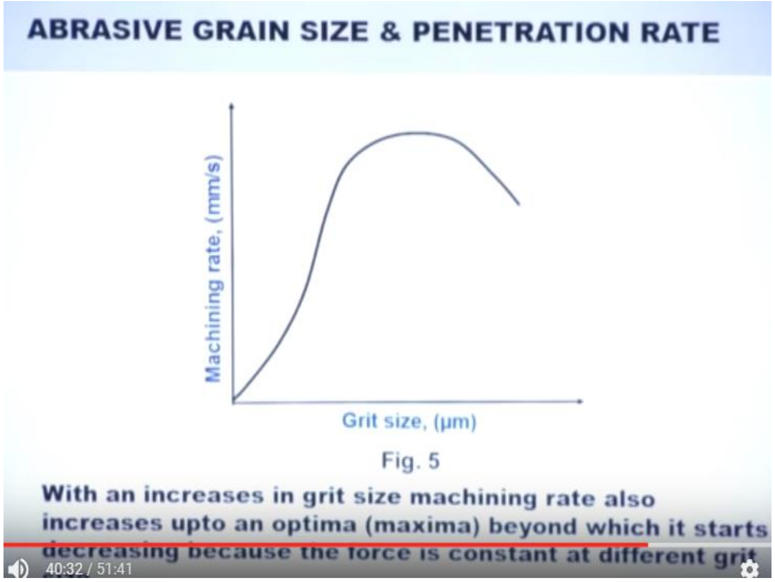

So grid size also affects the machining rate or penetration rate okay. With our increasing the grid size, size of the grid okay this penetration rate increases because bigger size abrasive particles hit and it generates higher volume of the chips okay or bigger volume of the chips but if we increase the abrasive grid size it reaches the optimum value okay but after some time we although we reach we although we increase the grid size then this machine rate decreases because energy however this total energy per movement okay so it is fixed okay.

Force is fixed here okay. So that is why whatever this energy it is distributed among the abrasive particles okay so when this bigger size abrasive particles are there now in that case there is a less the space less number of abrasive particle which is taking part into the machine okay. So then in that case also there is a reduction in the penetration rate. So that the force is constant so so that is why at different grid size okay so with the bigger although there is a bigger grid size but force is constant okay so that is why this penetration rate reduces okay.

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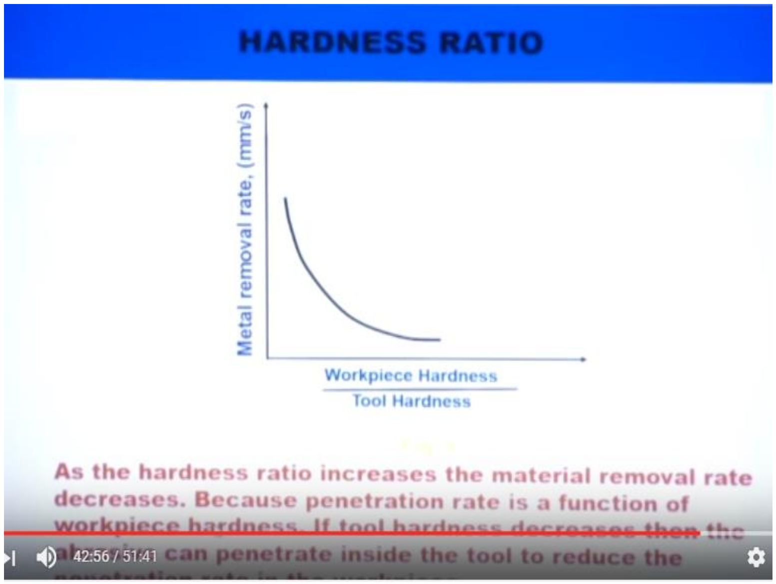

So this is the plot for tool wear rate relative tool wear rate means workpiece hardness divided by tool hardness will give the tool wear rate okay. So here in Y axis that is the metal removal rate or penetration rate. Now if we increase the wear rate or workpiece hardness by tool hardness okay so if we increase the workpiece hardness okay obviously your machine rate will reduce okay or if we increase the if we increase the if we decrease the tool hardness okay so in that case also your material removal rate will reduce.

So as the hardness ratio increases the metal removal rate decreases because penetration rate is a function of workpiece hardness. If tool hardness decreases then the abrasive can penetrate inside the tool to reduce the penetration rate in the workpiece okay. So this particle velocity also take part into the machining okay. So higher the velocity of the particle the machining rate will be higher because this kinetic energy whichever is gained by these abrasive particles it is utilized for the machining okay.

So this kinetic energy is 1/2 MV square okay so this kinetic energy so this particle velocity increases this kinetic because of this kinetic energy increases so machine rate also increases.

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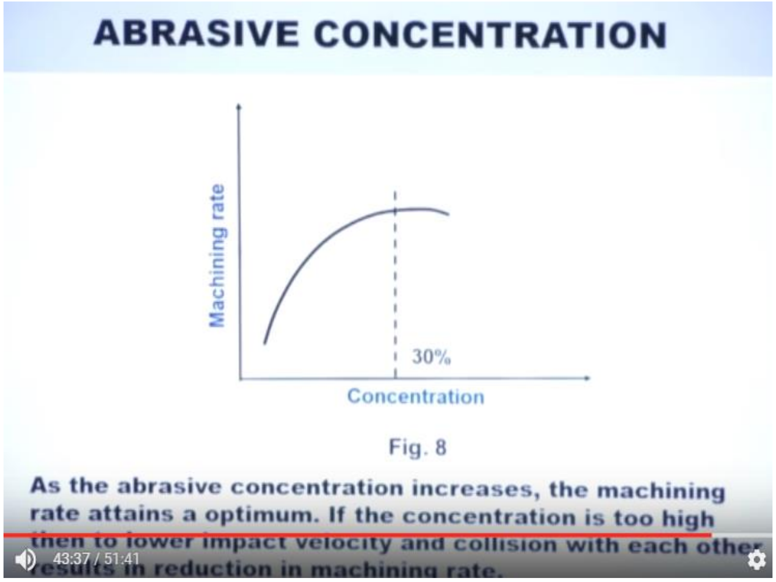

Okay concentration of abrasive particles okay so if we increase the more concentration more concentration of this abrasive particles okay so in that case machine rate or linear material removal rate increases but it reaches to an optimum level after that it slightly reduces or stabilizes okay.

If we increase the concentration of these abrasive particles beyond a certain level in that case whatever abrasive particles are there they collide with each other okay so they collide with each other okay so collision with each other results in reduction in the machining velocity. So when concentration of this abrasive particle is too high then lower impact velocity will be there because of this it collide with each other okay.

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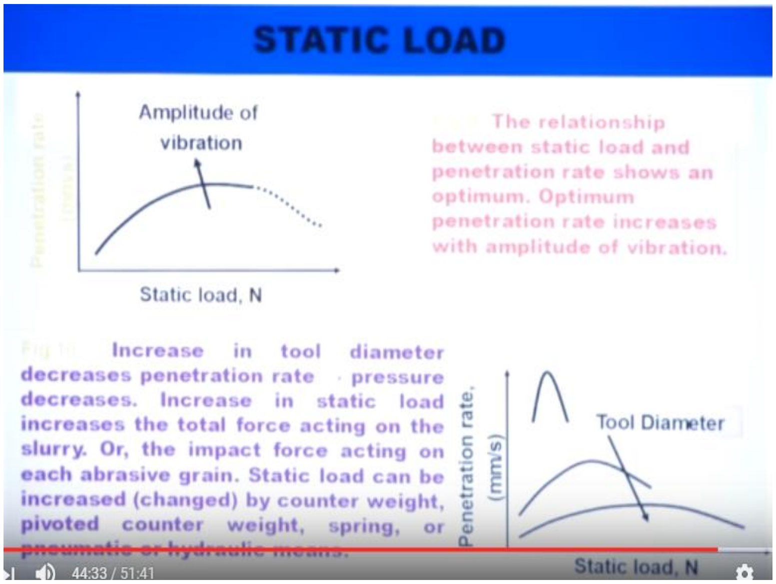

So here it shows the static load, so in the next slide we shall show how to give the static load okay. So this static load is constant for a certain for a single machining operation. For every experiment this static load is constant okay. So now if we increase the static load from from one experiment to next experiment if we increase the static load in that case penetration rate also increase but after some time after it reaches the optimum level then it reduces okay.

So this is the relationship between static load and penetration rate source and optimum value. So optimum penetration rate increases with the amplitude of vibration or if we increase the amplitude of vibration then optimum penetration rate also means so it increases okay the optimum static load it increases with the increasing the amplitude of vibration.

So here every curve so we are using we are wearing the static load here so here also static load but here tool diameter actually increasing okay, tool diameter is increasing in the bottom reduction so here it is lower tool diameter this one is the bottom bigger tool diameter. So with the lower tool diameter penetration rate is high for bigger tool diameter this penetration rate is less okay. So increasing the tool diameter decreases the penetration rate. So here we are increasing the tool diameter the penetration rate decreases.

So because this pressure decreases okay so increase in the static load increases the total force acting on the slurry but the impact force acting on each abrasive grain static load can be increased by counter weight, pivoted counter weight, spring, or pneumatic or hydraulic means okay. So next slide we shall see what are the different way we can give the static load okay.

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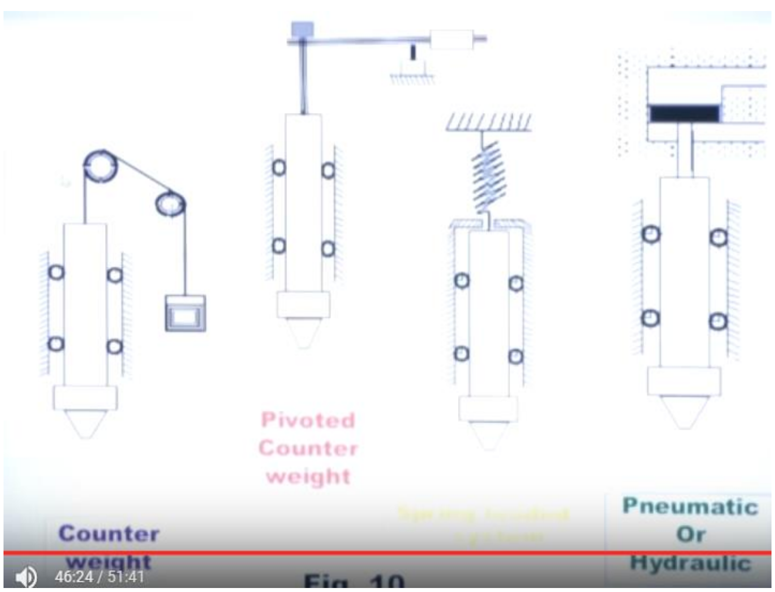

So this is one one process for giving the static load to this tool so this one is the counter weight is generating by changing this counter weight we can change the load given to the tool.

So this one is the pivoted counter weight is used. So using this pivoted counter weight we can give the load to the tool. So this one is the spring loaded system so using different spring constant okay different kinds of spring with a constant of elasticity different constant of elasticity okay so we can change the tool we can change the load on the tool okay so now another way of giving load is pneumatic or hydraulic okay so by using this pneumatic or hydraulic coil with pressure we can change the load static load on the tool.

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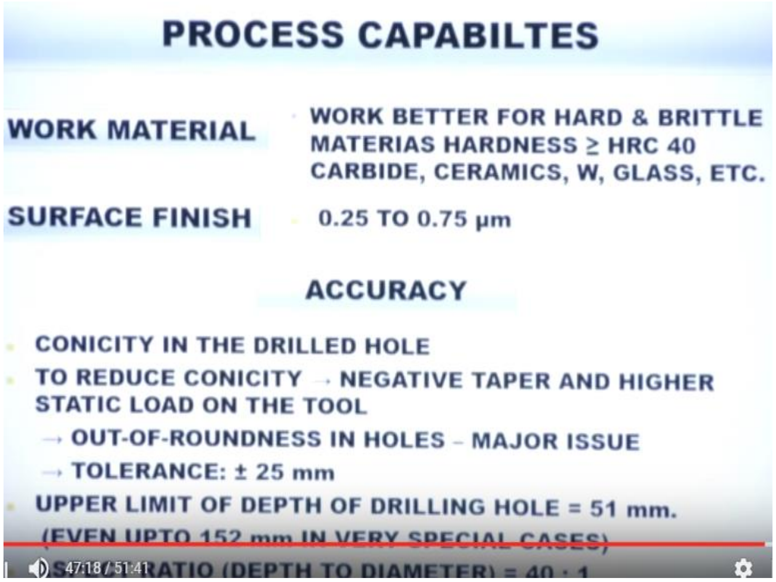

So process capability is a very important thing. So what what is the capability of the process okay. So what material so it it works fine for hard and brittle material because initially I told it because it brittle it makes the brittle fracture into the workpiece surface. So machining is well done by brittle fracture so hardness in Richter scale C scale okay sorry local hardness HRC local hardness it should be more than 40, local hardness in C scale it should be 40 okay. So this carbide, ceramics, tungsten, glass. These are the materials which are used for this as a work material.

So surface finish is achieved by this ultrasonic machining is 0.25 to 0.75 micron okay. So accuracy also is an important parameter okay. Conicity of the drill hole is there. So you can see that one after machining this ultrasonic machining if we are doing cylindrical hole we can see this kind of conical shape or hole is generated because of this sidewall machining okay. So to reduce the conicity we have to develop different kinds of mechanism so one is the reverse shape of this tool. It can take the shape of this tool like this okay reverse so that it can reduce the the sidewall machining should be reduced okay can be reduced.

So this is called negative temper and higher static load on the tool if we use higher static load in that case also conicity can be reduced. Out-of-roundness of the hole so out-of-roundness we know out-of-roundness is suppose a circular thing is there so you can consider the pen it is a circular cross section although in naked eye it is shown as a circular but if you see under microscope or if you attach a probe there one machine is available so you can see this is not perfectly circular so in that case we can it is not perfectly circular so in that case there is a means in between this circumscribe and inscribed circle this mean circle passes through this circumscribe and inscribed circle okay so this gap between these two is called the out-of-roundness.

So this out-of-roundness is a major issue. So in ultrasonic machining this out-of-roundness is a major issue in case of ultrasonic machining. Okay tolerances of this force are generated plus minus 25 micron. So upper length of the depth of the tool depth of the hole is generated as 51 mm. Even up to 150 mm in very special cases can be generated and aspect ratio can be achieved up to 40:1 which is very high.

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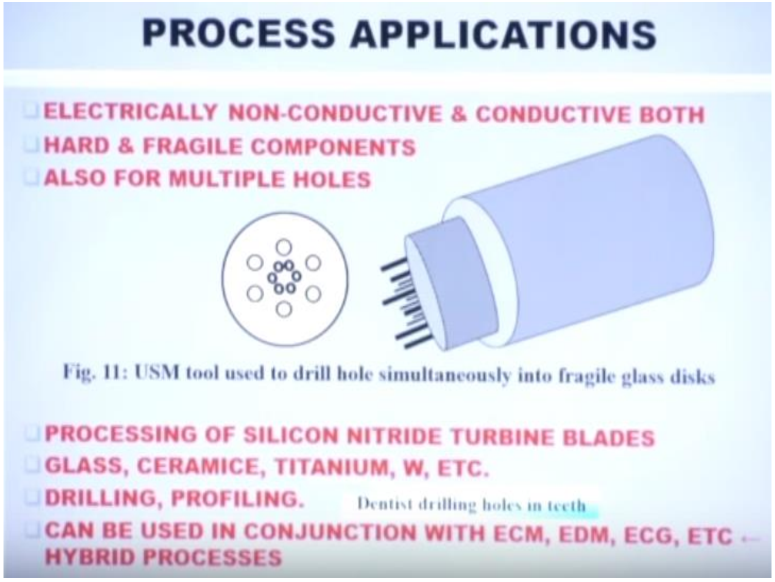

So process applications so it this machining process can be used electrical conducting and non-conducting material okay. So any kind of material we can machine but the materials would be brittle and hard material so that there is a brittle fracture can be done okay.

So hard and fragile components very thin components fragile components like glass, quartz can be machined by this process which is not possible by conventional machining any conventional drill or milling machine. Also multiple holes can be generated by this process, multiple holes can be generated to increase the efficiency of this process we can generate multiple holes, thousands of holes can be generated by a single operation.

So processing of silicon nitride turbine blades. So this turbine blades there is a cooling channels are there okay and some holes may be generated for fixing purpose that can be done by this ultrasonic machining process. Glass, ceramic, titanium, tungsten these kind of materials are machined. So drilling, profiling done by this process can be used in conjunction with the ECM, EDM, ECG electrochemical grinding so we can use we can use as a this one in conjunction of other process as a hybrid process okay.

So thank you.