Advance Manufacturing Processes

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Module - 3
Advanced Machining Processes
Lecture - 6
Mechanism, Processes Variants and applications of USM

Welcome to this another session on ultrasonic machining under the course advanced manufacturing processes. In the last session we have discussed about the basic features in ultrasonic machining process, the machine used and its subcomponents. Also the suitability and tooling was also discussed briefly. In this session we will mainly study about the tool holders and tooling requirements, the mechanism of material removal, process parameters that affects the quality of the machined surface in ultrasonic machining, then some variants in ultrasonic machining process as well like we have discussed in some other processes, then applications of ultrasonic machining process.

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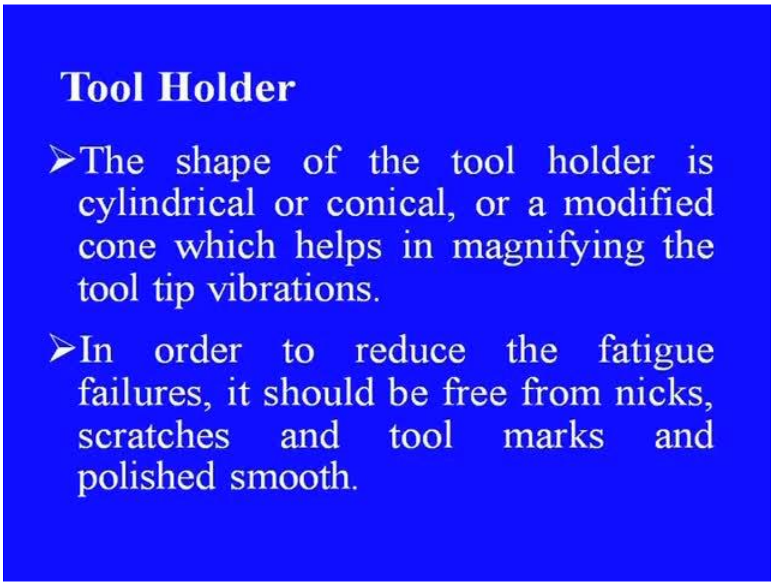

Let us look at the tool holder which is considered to be one of the important components in this system. The shape of the tool holder is generally cylindrical or conical or a modified cone which helps in magnifying the tool tip vibration. Thus, the shape of the tool is determined according to the optimization of the tool vibration. In order to reduce the fatigue failures it should be free from nicks, scratches and tool marks and polished smooth.

Now, let us see the design of the tool. The tool materials should be tough and ductile, this has been already told in earlier sessions. Then accordingly low carbon steel and stainless steel, these are the some of the materials that give good performance as far as the ultrasonic machining is concerned. Tools are usually 25 millimeter long in its size and its size is equal to the whole size minus twice the size of the abrasive. This is basically like this.

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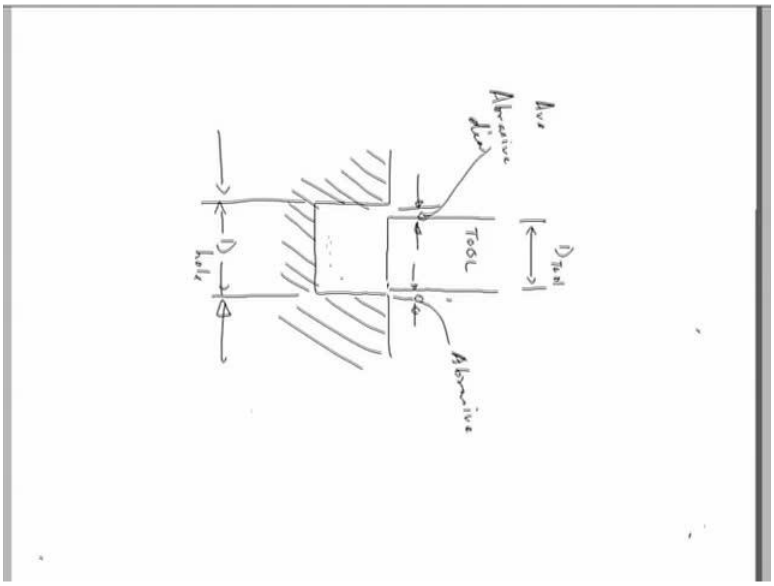

If this is the hole to be produced then tool should be such that this is the hole size and this is the difference side wise, this would be the difference, here this is the tool and this is considered to be the work piece and this is the size of the say tool sorry hole diameter, then tool diameters should be say this is the tool and this is the hole. It should be one diameter edge side of the abrasive particle. This is abrasive and this abrasive.

So, this is average you can say average abrasive diameter. Therefore, so that the abrasives can enter and the abrasives here after doing the work or cutting here can come out through this. So, this is basically followed while designing a tool in case of USM. Mass of the tool should be minimum possible so that it has not absorb the ultrasonic energy. Then what are the other requirements of the tool?

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It should have high wear resistance, should have good elastic properties, it should have high fatigue strength as it will be continuously subjected to fatigue kind of loading under very high frequency, then it should have optimum strength because this will have to under the withstand the impacts the abrasive particles as well and abrasive particles are of usually very high strength materials, hard materials like silicon carbide or boron carbide etcetera and then it should have also optimum hardness. Let us see a semantic representation of this USM apparatus like this.

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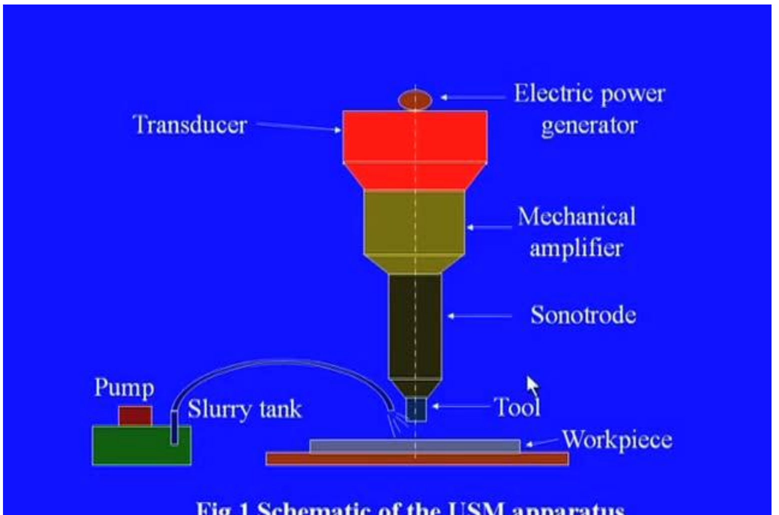

Fig.1 Schematic of the USM apparatus

So, this is the apparatus is in the screen. Here, basically this is the work piece to be machined either drilled or cut or whatever and this is fitted on the work table. This work table will be in generally it will be part of the entire machine setup. It will be integral part of this machine setup and in some cases this work table can be made the computer numerical control as well, so that we can have a better control or numerical control on the size of this or on the movement of this work piece.

Then this is the slurry system where the pump and the filter and stirring arrangement will be there and this slurry will be made to flow to this machining zone, machining zone with the help of some hose arrangements and the pump. This can be, the flow rate can be control by proper control here. Then apart from this the main structure of this setup is something like this. So, wherein the electrical power will be provided and the transducer will be responsible for converting this electrical power into the mechanical vibration.

This mechanical vibration will be further amplified and this sonotrode will be responsible for coupling this mechanical vibration to the tool tip. And finally, we will be observing the net result that is the oscillation, mechanical oscillation at this tool tip. So, this arrangement is for coupling, then conversion of electrical energy into mechanical energy and then amplification of this mechanical vibration to a desired level.

And this vibration can also be controlled by appropriate control mechanisms of this electrical power and so on. Further along with this vibration or the frequency of oscillation we can also control the amplitude at which it is vibrating. That arrangement can also be made in this control system. Coming to the movement of the tool in USM process so during one strike the tool moves down from the most upper remote position which is starting speed at 0 then its speeds up to finally, reach the maximum speed at the mean position. Then the tool slows down its speed and eventually reaches the 0 again at the lowest position.

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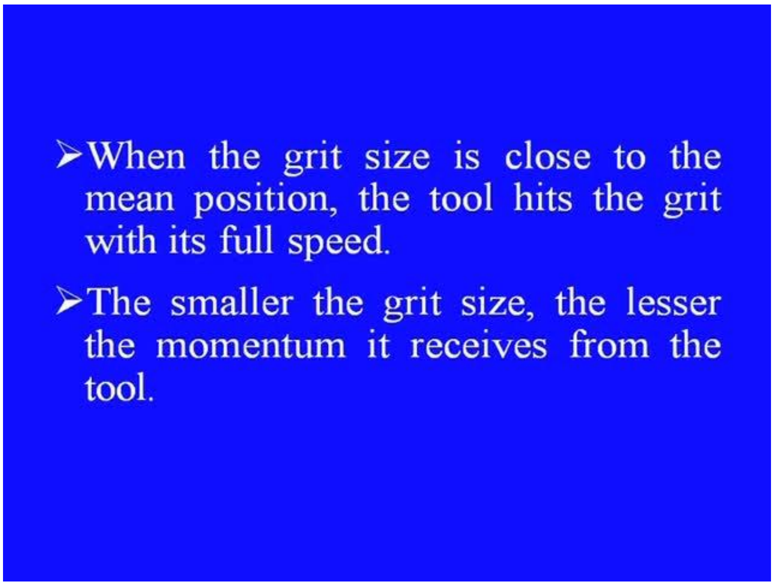

When the grit size is closed to the mean position the tool hits the grit with its full speed and smaller the girt size the lesser will be the momentum it receives from the tool. The forces induced due to vibration are shown in the sinusoidal wave form. The areas under the cover can be assumed to be triangle to enable solving it in the form of an equation, this is explained in the following figure.

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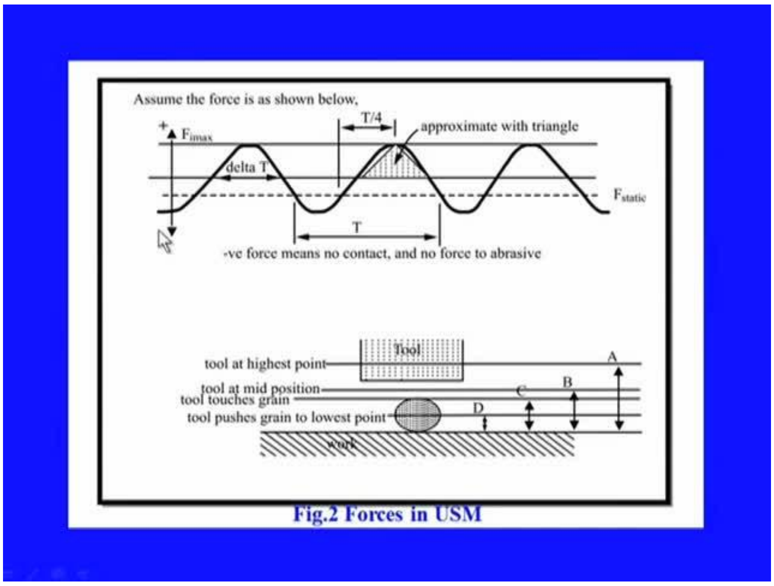

Fig.2 Forces in USM

So, this is, this is how the variation of the force will take place. So, here force will be maximum and this will move from maximum to minimum and this is the delta T and this will be approximated with a triangular shape. And this is the schematic of the tool position with respect to the abrasive as well as the work piece. So, this is considered to be the lower most position an abrasive can have where the tool can hit it before going inside the or before making the indentation on the work piece.

So, this is the top most position where the tool will start getting accelerated and this is the mean position, mean position where tool will attain its maximum velocity. Then again it will start decelerating and when it reaches here so this is the minimum position it it comes to and then it starts pushing the pushing the abrasive material against the work piece surface here. And the abrasive will move through or penetrating this work material here after. Thus, if we go into mathematics of this; what happens? So, after simplification the force equation reduces to be something like this.

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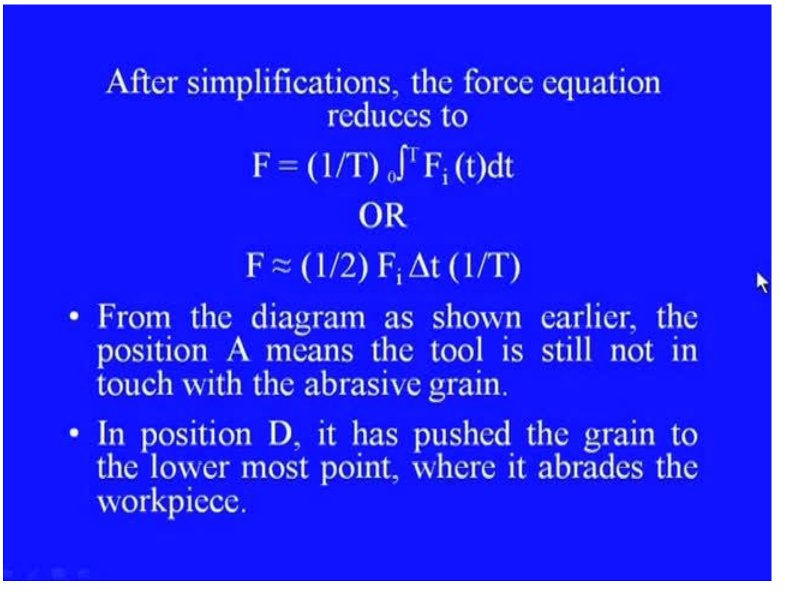

This is F equal to 1 upon T then integration of F i, F is the force at at a time instant T which is integrated from 0 to time T. The T we have seen in the previous slide. So, T is this duration, this is delta T and this is T total one cycle of this. So, within one cycle what is the variation of the of the force? So, from this diagram the position A means the tool is still not in touch with the abrasive grain and the position D is it has pushed the grain to the lower most point where it abrades the work piece. So, these positions are shown here, this is the lower most position and this is the top most position A.

Now, let us have a look at the abrasive slurry, detail look on it. The recommended slurry to be used in this process is a mixer of abrasive particles and liquid. This liquid can be water which is most widely used, which is low cost, easily available and environment as well as the operator friendly and of course, kerosene can also be used. This is also a low viscosity fluid and therefore, this can also be used. Of course, fire hazards or health hazards are associated with this liquid. The slurry is pumped across the tool face. Slurry pump is a part of the machine system as we have seen already.

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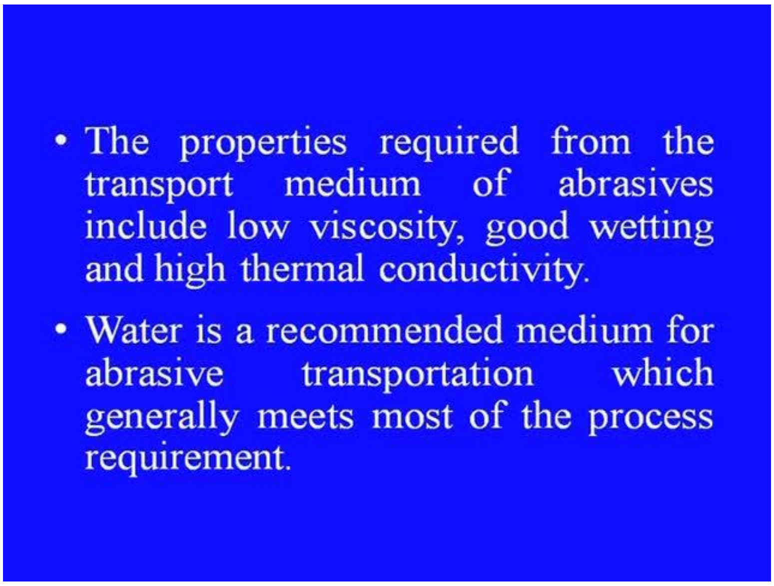

The properties required from the transport medium of abrasives include low viscosity, good wetting and high thermal conductivity. This is because while impacting there will be a localized heat development where the exactly the abrasive materials will hit the work piece, there will be a localized development of the heat or temperature rise will be there. And this heat should be take away by this medium quickly otherwise the softening of the material will take place; softening of the work tool material may take place and that will bring down the efficiency of the process.

Further, as we know this process is basically works on the brittle fracture of the material and if the material gets softened there would not be the brittle fracture condition prevailing anymore. Water is a recommended medium for abrasive transportation which generally meets most of the process requirements.

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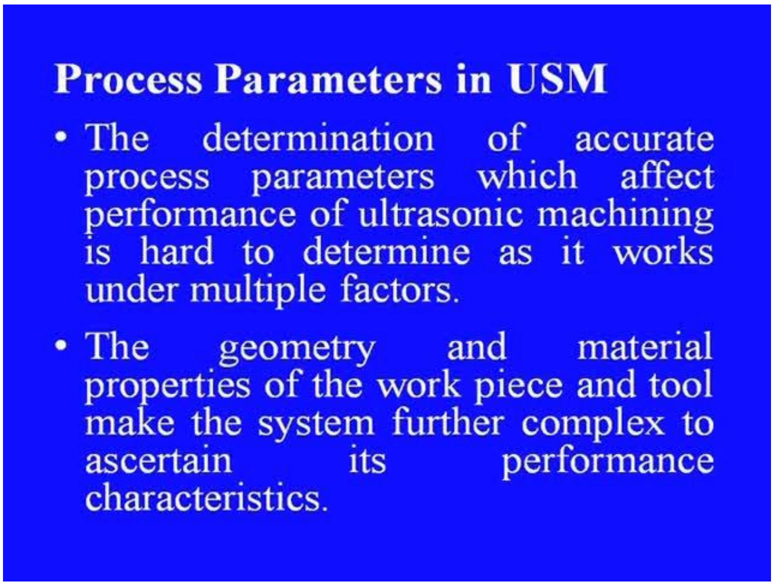

Now, let us look into the process parameters that affects the USM process ultrasonic machining process. The determination of accurate process parameters which affect performance of ultrasonic machining is hard as it works under multiple factors. Already, we have see there are as many as four known mechanisms that could take place during ultrasonic machining.

Therefore, what exactly the parameters, number of parameters and to what extent they are having the influence, quantifying them and the quantum with which they are acting on the process is very difficult to determine. So, the evaluation process or the assessment of this is very, very time consuming, very expansive and I am afraid at most of the time we do not have the requisite equipment also for that. The geometry and material properties of the work piece and the tool make the system further complex to ascertain its performance characteristics.

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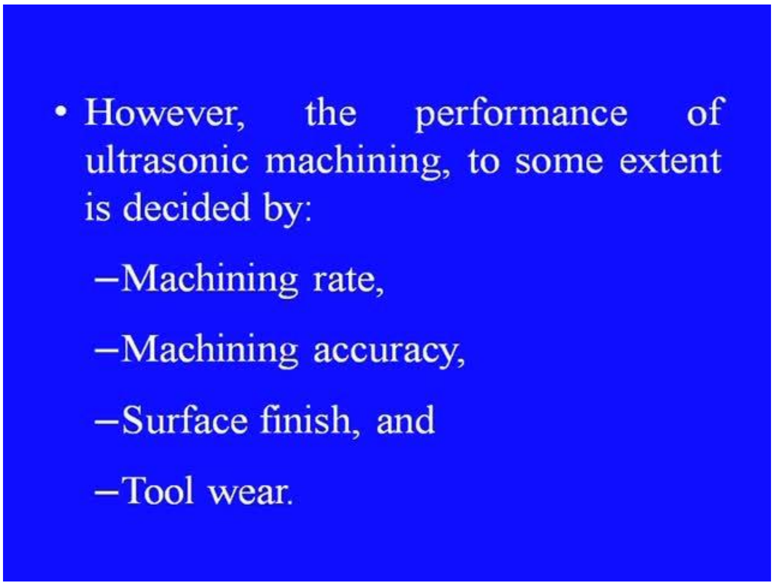

However, the performance of ultrasonic machining to some extent is decided by the machining rate, the machining accuracy, surface finish and tool wear. Machining rate is always important as far as the productivity is concerned and as far as the quality is concerned machining accuracy and surface finish both are very very important to meet the standard, to meet the quality and to meet the expectation of the customers this parameters are very, very important.

And of course, another operating parameter is like tool wear which which is unseen to the costumers, but which is very, very important as far as the operation is concerned. If tool wear is very high the down time of the machine will be very high and the cost will be, cost corresponding to this will be very high. Therefore, low tool wear will be indicative of better performance of the process.

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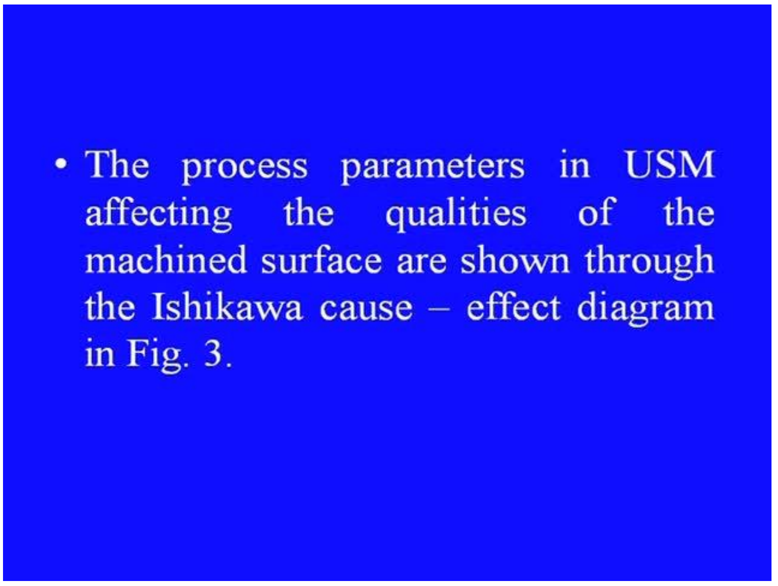

The process parameters in ultrasonic machining affecting the qualities of the machine surface can also be represented in an Ishikawa cause effect diagram.

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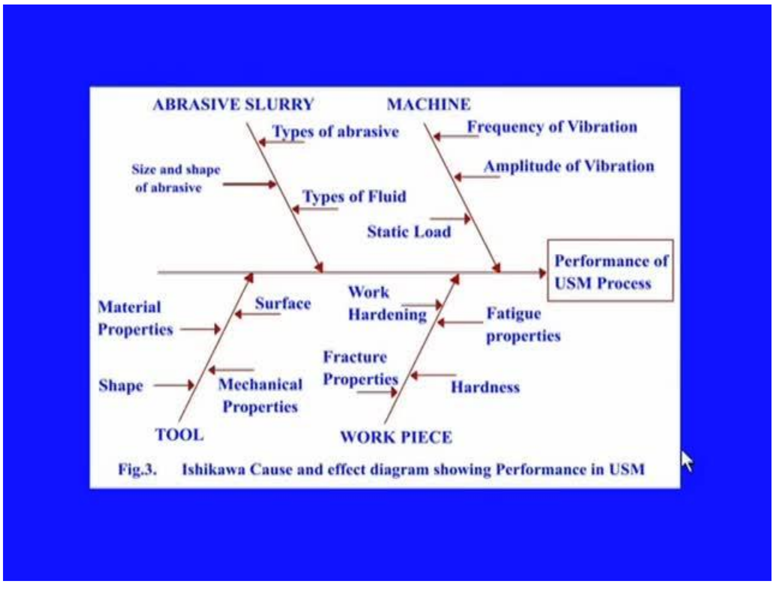

Like this in which four different major categories of parameters are shown, those are abrasives slurry based parameters, then machine based parameters, tool based parameters and work piece based parameters. In abrasive slurry based parameters types types of fluid, size and shape of the abrasives these are important. In machine based parameters frequency of vibration and the amplitude of the vibration then the static load these are important parameters that affects the quality or the performance. Then as far as tool is concerned as we have already discussed tool material is very, very important.

So, the properties of the tool material is important criteria, then shape of the tool material, then the mechanical properties of the tool material, strength etcetera hardness and then the surface. Then work piece related parameters are like work hardening, then fracture properties, hardness etcetera. These process parameters affect the performance of USM can be arranged in this four categories like abrasives slurry, machine, tool and work piece based parameters.

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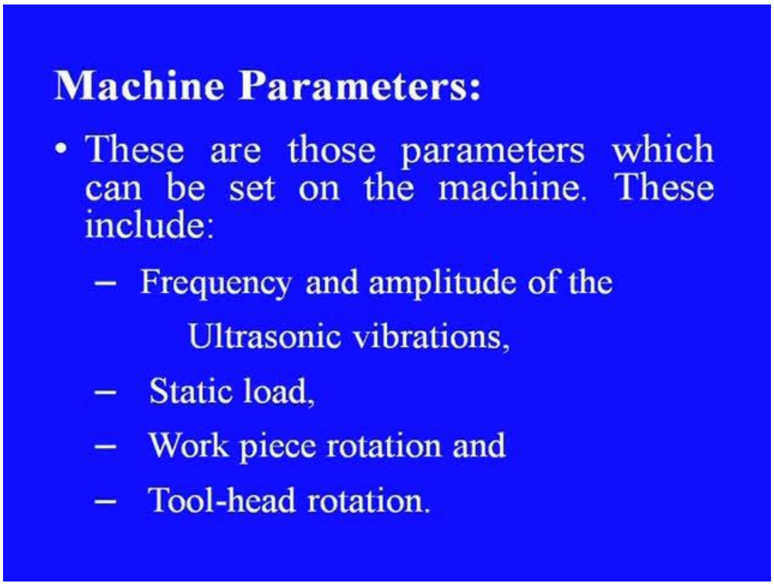

In this machine based parameters frequency and amplitude of ultrasonic vibration is is most important as far as the working of the entire machining is concerned. Then static load of course, which influences the material removal rate, this is also very important. Then work piece rotation, in some cases the work piece also can be made to rotate so that the flushing becomes more effective and the corresponding material removal becomes more. Then tool head also can be made to rotate, again to enhance the capability of the machine or the performance of the machining process.

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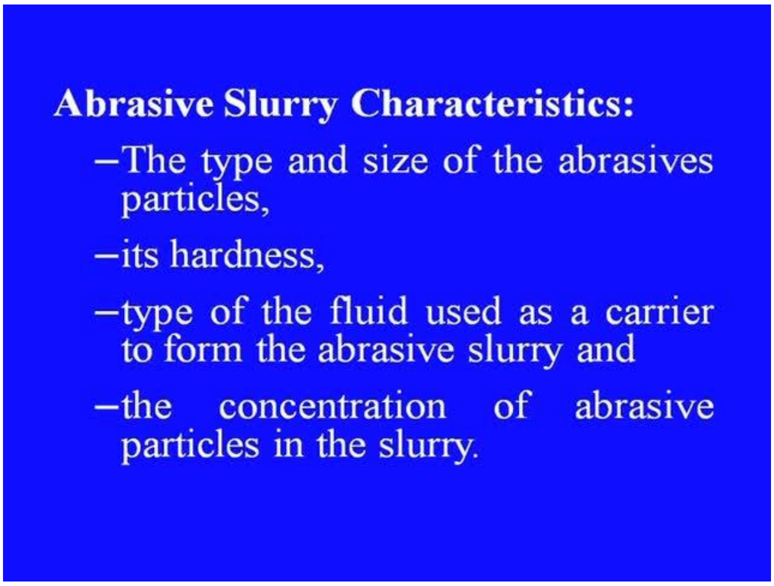

Then abrasive slurry characteristics should be like the type and size of the abrasive particles, there hardness, then the type of the fluid used as a carrier to form the abrasive slurry and then concentration of the abrasive particles in the slurry. These things are very important as far as the characteristics of the abrasive slurry is concerned. As far as the work piece properties are concerned the following properties affect the performance.

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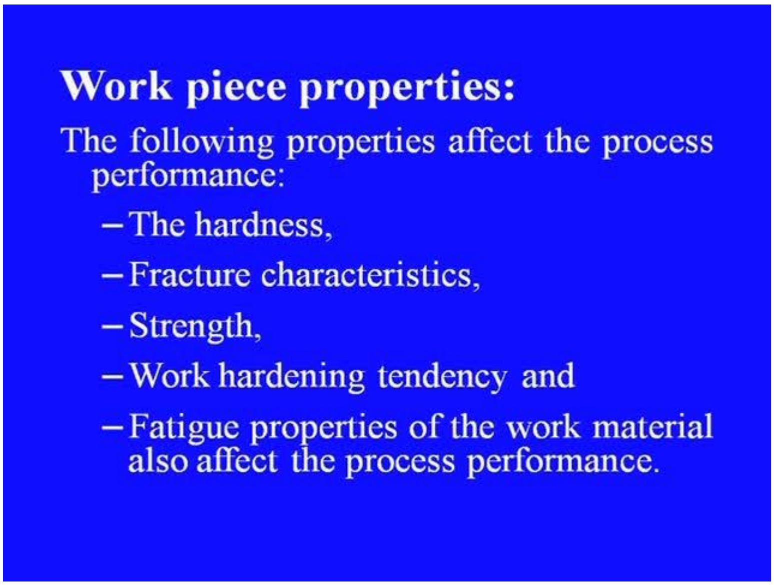

The hardness, fracture characteristics, strength, work hardening tendency and fatigue properties of the work material. These are some of the parameters that affect the process performance like for example, if the hardness of of a work material is less and it is more ductile then the performance will come down as we know this entire material removal depends mostly on the brittle fracture of the material and in in case of ductile material the material will tend to flow rather than fracture and therefore, the material will flow side wise rather than getting removed or sheared fracture from the work piece original material.

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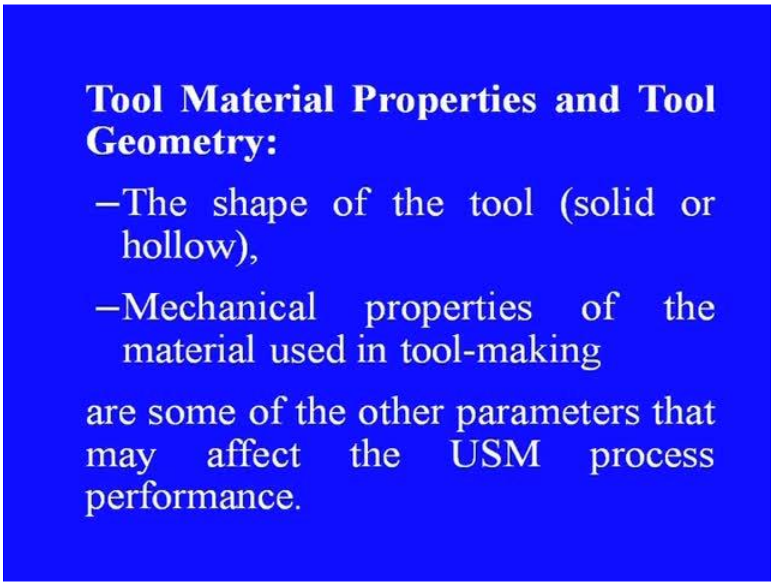

Then let us see the tool material properties and the tool geometry. The shape of the tool whether it is a solid tool or it is a hollow tool in both the cases the performance will be different. The some hollow tool will tend to get worn out very fast whereas the solid tool will give better tool life as far as the wear is concerned.

Whereas in case of hollow tool probably if we are going for a true hole then it can give better result as the machining area will be less and therefore, the entire tool and machine will experience less load in due course of time. Similarly, the mechanical properties of the materials used in tool making that is also important as far as the tool material and tool geometry is concerned and this will affect the process performance. Now, let us look into the capabilities of this ultrasonic machining process.

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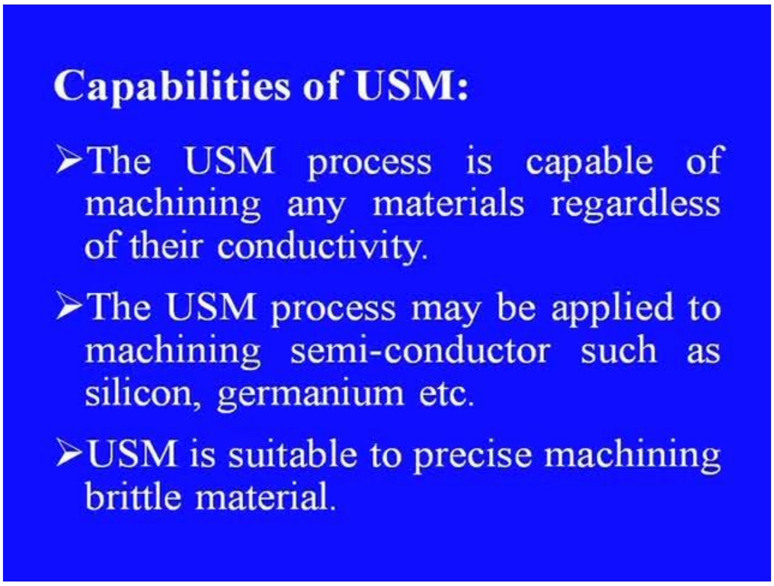

The USM process is capable of machining any materials regardless of their conductivity. The USM process may be applied to machining semi conductor such as silicon, germanium etcetera. In fact in the semiconductor industries this ultrasonic machining processes very widely used. Ultrasonic machining is also suitable to precise machining of brittle materials; this has been discussed repeatedly so many times.

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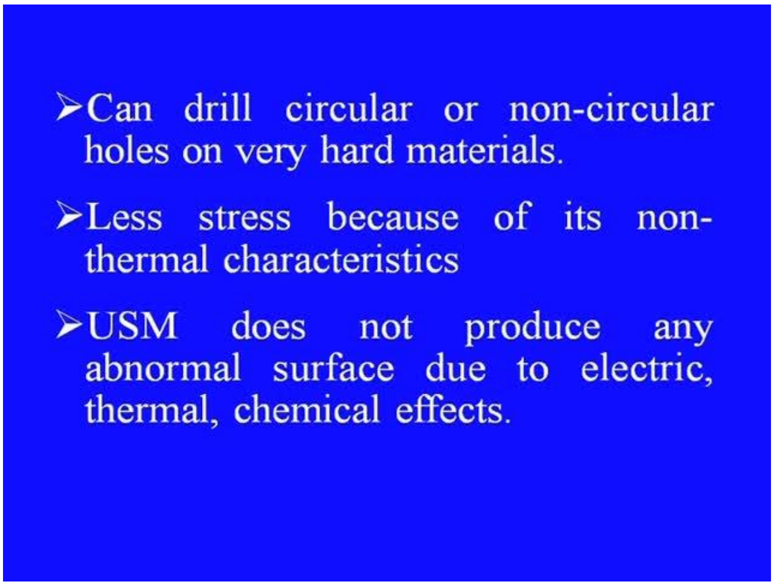

Then it it can drill circular or non circular holes on very hard materials. Less stress is developed because of its non thermal characteristics. Also, USM does not produce any abnormal surface due to electric, thermal or chemical effects. Excellence surface qualities with average roughness less than 0.2 micro meter can be achieved which no, with normal machining conditions in this process. The USM process can be controlled using intelligent control algorithms, thereby safety can also be ensured. Protection of work piece and tool can be achieved because of reduced contact forces and low thermal stress.

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Self sharpening diamond tools guarantee high removal rates at low contact forces and long service life. Water is coolant and cleaning medium with excellent ecological compatibility can be achieved, as we know water is the main working fluid in this system ultrasonic machining system.

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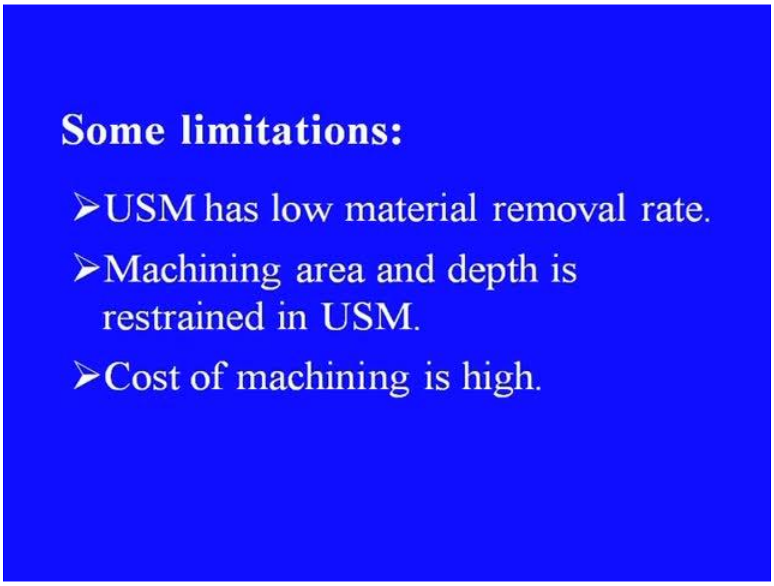

Now, let us look in to some limitations as well. Ultrasonic machining has low material removal rate, this is inherent to it. Machining area and depth is restrained in USM. Then the cost of machining is high. Regarding the the restraining of the machining depth we can see it like this.

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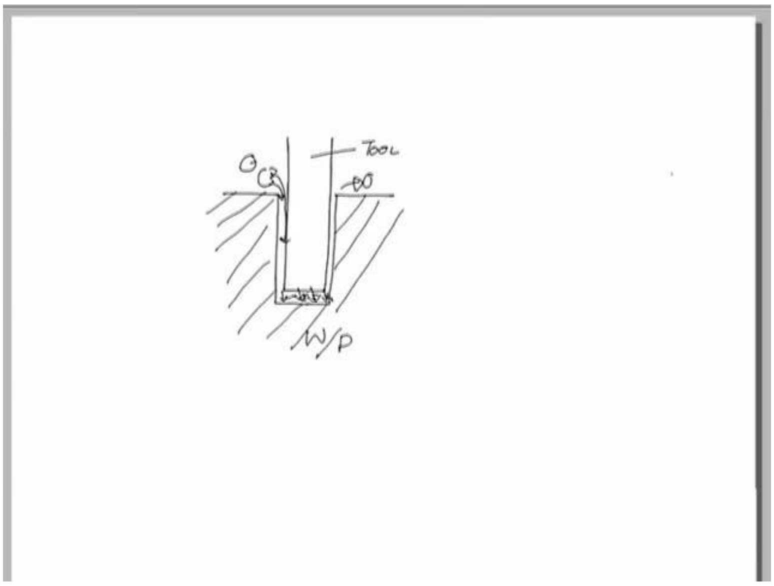

So, this point can be explained like this. If a hole with high aspect ratio is to be drilled with this process say this is the work piece, my work piece then the tool should move like this by a considerable distance inside this work piece. So, this is the work piece.

Now, there will be difficulty in these abrasives coming through this and getting flushed out like this or similar case. Therefore, if the fresh abrasives cannot enter into this, this zone where the actual, the machining is taking place. The machining is taking place here only.

Now, if the fresh abrasives cannot reach this zone then the cutting performance will not be good and not only these abrasives should reach this position, but also this need to be flushed out from this position so that fresh cutting edge can come into this, enter into this. Therefore, this is inherent we can say a defect or inherent limitation of this process where very high aspect ratio holes cannot be drilled in an in an efficient manner. Under ideal conditions penetration rates of 5 millimeter per minute can be obtained. Power units are usually 500 to 1000 watt output units.

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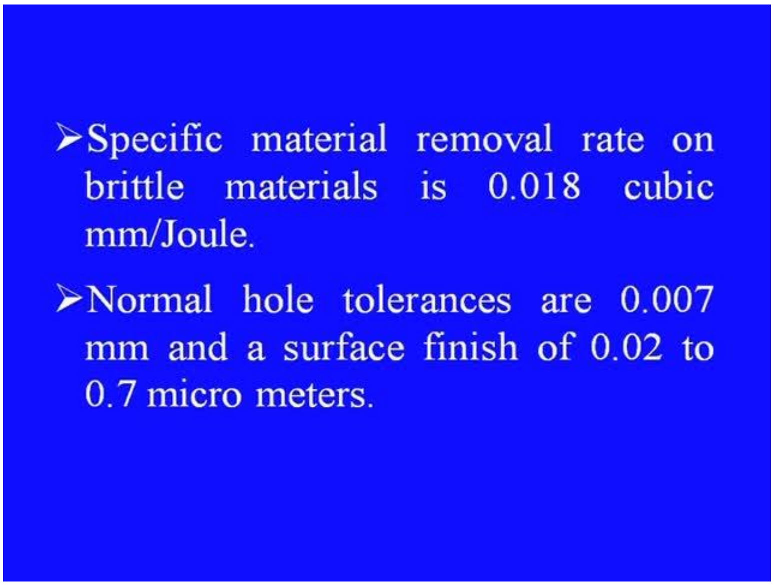

And in these process specific material removal rate on brittle material is 0.018 cubic millimeter per joule can be obtained. Normal hole tolerances are 0.007 millimeter and a surface finish of 0.02 to 0.7 micro meters can be obtained. The following figures show some of the capability of this, this process.

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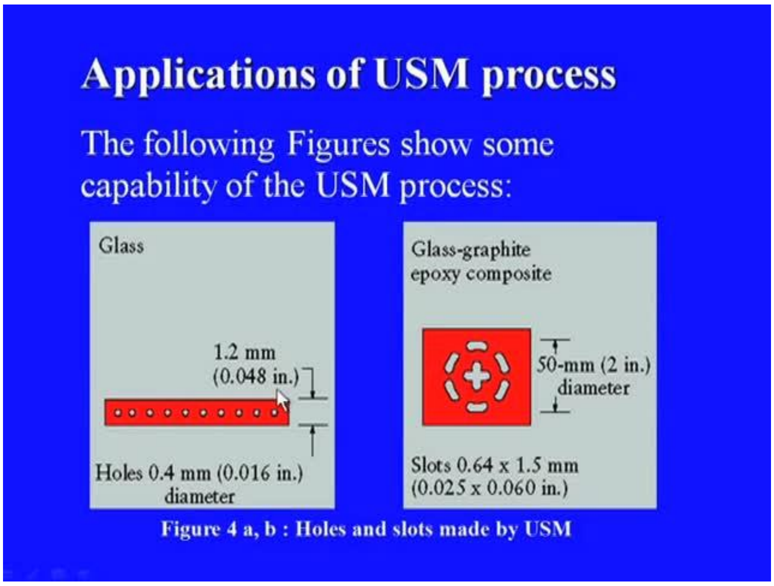

So, here this is a strip which is having 1.2 millimeter thickness only and within this 1.2 millimeter thickness holes of 0.4 millimeter diameter are being drilled using this USM process. This talks about the performance or capability of this process that such a small holes can be drilled effectively on such a small strip of material. Again, this another application or machining example in which only 50 millimeter diameter material or a strip having 50 millimeter width and here number of slots are being cut using this ultrasonic machining and its slot measures 0.64 into 1.5 millimeter in dimension.

Thus, this also talks about the versatility of this process and its usefulness in various small machining applications as well or micro machining applications as well. We will see some of the developments in micro machining using this micro ultrasonic machining in another session.

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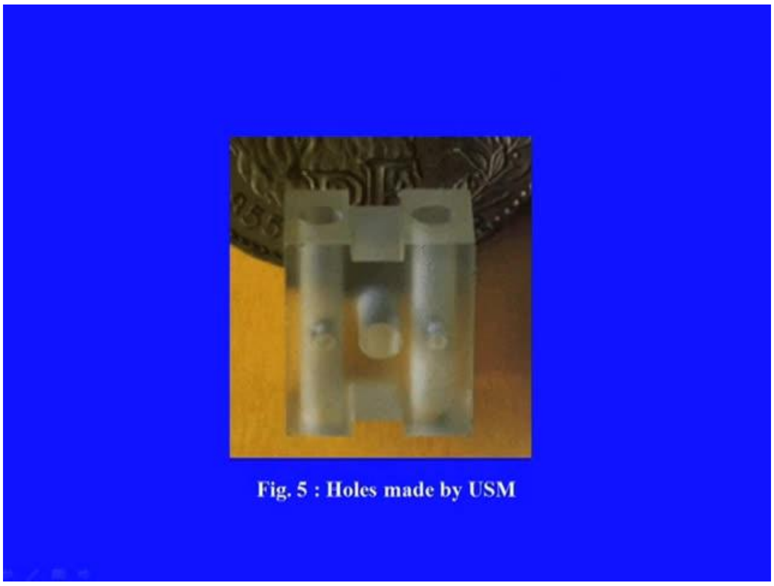

So, this is a typical hole being produced by this ultrasonic micro machining. So, here very small holes are being drawn. Now, let us move into the effect of process parameters. We will look into the major process parameters which are being investigated very widely and the effect of these parameters on surface produced as well as on the material removal rate we will try to explore.

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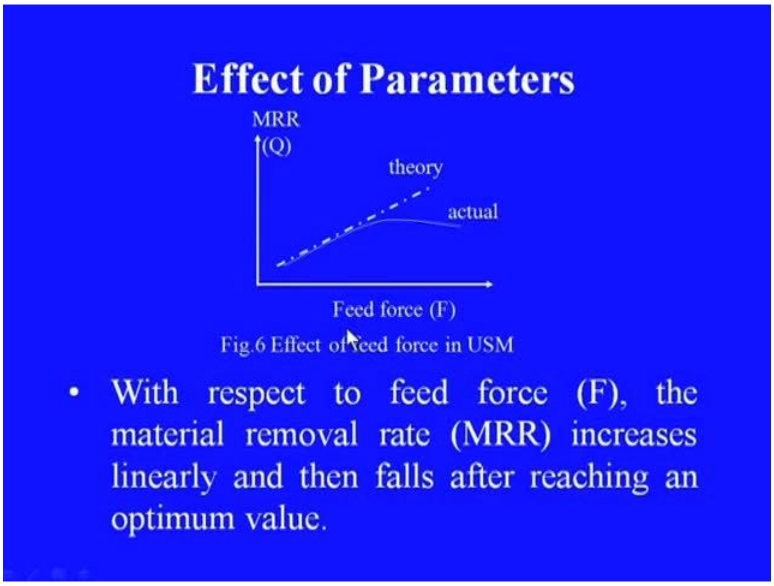

So, here as far as the feed force is concerned this is the characteristic actually this happens and this is what is theoretically it should look like. That means as the feed force increases the material removal rate also linearly should increase at the same rate, theoretically. However, it was found that beyond the certain optimum force, feed force this slightly drops down that means this indicates that there is an optimal feed force to be applied and if the feed force is higher than this then probably the crushing of the abrasives that take place instead of machining of the work piece. So, that may be the reason why this material removal rate comes down with very high feed forces.

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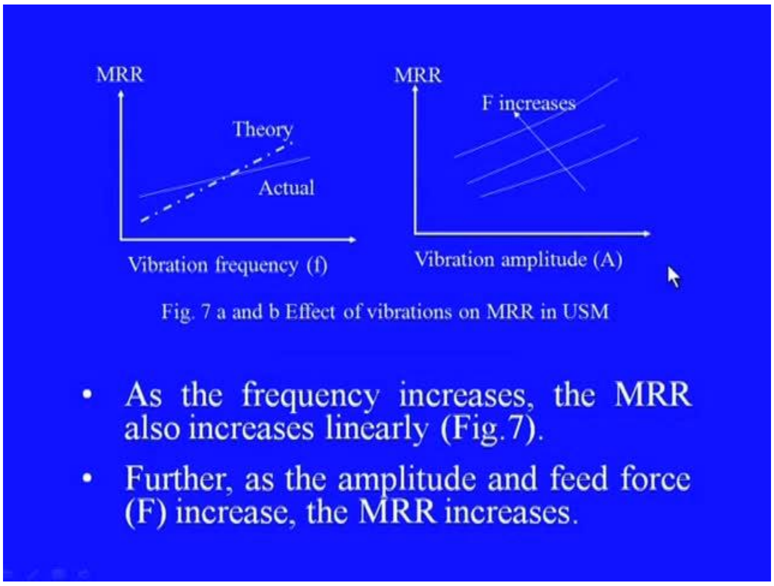

These are another two characteristics as far as the vibration frequency is concerned and as far as the amplitude of this vibration is concerned. How do they affect the material removal rate in this? So, here also theoretically if we see the as the vibration frequency increases the material removal rate should increase and in fact it increases, but not at the same rate. The, it is it is bit sluggish as the frequency is increased the material removal rate does not increase at the same rate, it is bit sluggish.

However, as far as the amplitude is concern so here also in this case also with amplitude, increase in amplitude the material removal rate increases and if we see along with that the feed force. Then with feed force this rate, material removal rate further increases. If we increase forces, feed forces like this then the rate of material removal becomes higher still higher with increase in amplitude.

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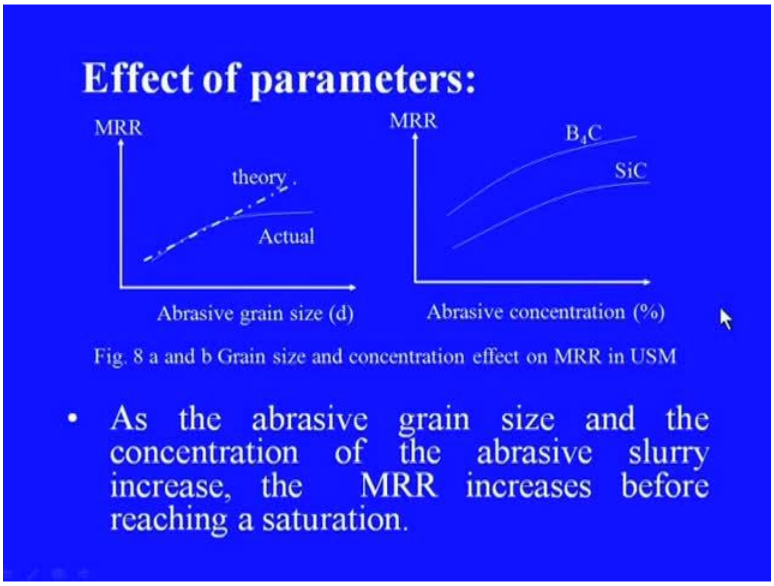

This figures show the characteristic of material removal rate with respect to grain size and abrasive concentration in the slurry medium. The grain size also we have seen a very peculiar situation like up to a particular optimum grain size the material removal rate increases with grain size. However, beyond that grain size or grain diameter we can say, say for in this case it is something like this, the material removal rate do not increase appreciably. Rather it remains almost same, that means there is an effective limit of the grain size also which we can use in this process, may be beyond certain sizes the grains will not come into the actual working zone or the cutting zone will not reach there and therefore, the cutting will stop.

Then as far as the abrasive concentration is concerned so this is also showing that as abrasive concentration increases that means the percentage of abrasive present in a particular volume of slurry media then the material removal rate also increases. However, again the same thing happens beyond particular optimum level the increase sizes or the rate of increase comes down appreciably rather it shows a tendency of saturation as we can see from here. It shows some sort of saturation tendency. This is because as the concentration increases then rather than the abrasives hitting the work surface they them self hit and that causes the fracture on them, this can be explained something like this.

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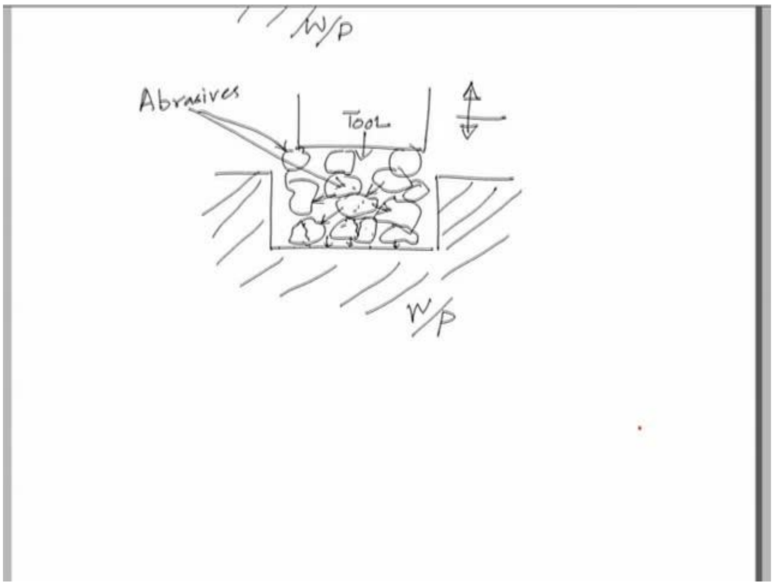

If this is the work piece and these are the abrasive and if the abrasive concentration is too high in the cutting zone, this is tool which is hitting this abrasives in this way or you can say this is oscillating like this, then instead of these abrasive, abrasives hitting this work material effectively this each of this abrasives. So, these are nothing but abrasives so they them self will hit each other.

So, like this. So, this will hit this, this will hit this, then this will hit this probably and then the this abrasive materials will get fractured into smaller parts rather than they are doing work on this work material or hitting this work material they them self will get engaged in hitting each other. And therefore, the cutting efficiency of material removal efficiency will come down appreciably or at least we can say they do not, it does not show any increasing tendency any further. So, this is what is explained by this saturating tendency of these curves. Next, parameter is the viscosity. We are talking about slurry. Slurry is one of the important component in this system.

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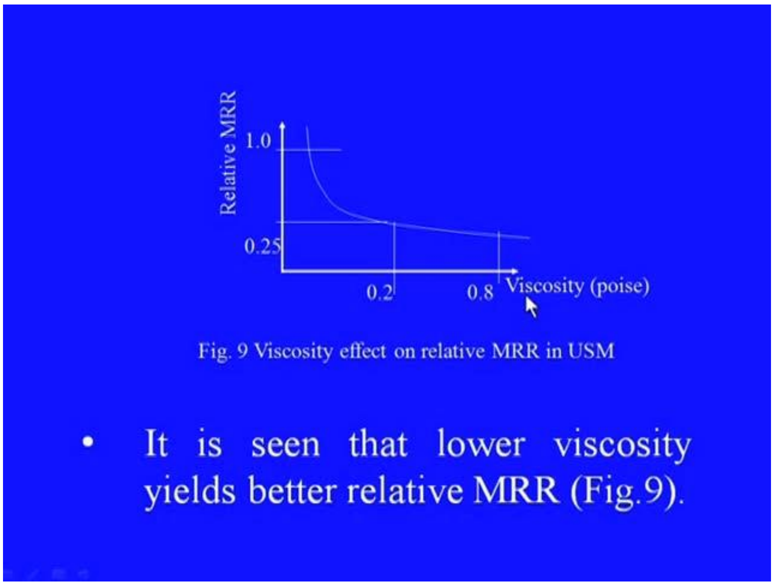

And if the, this particular characteristic shows the, as the viscosity increases as the viscosity increases the material removal rate decreases which is quiet possible because as the viscosity increases the movement of the particles the abrasive particles in this medium becomes sluggish. However, as we know the efficiency of cutting will depend upon how fast these abrasive materials can hit the material in that cutting zone.

Therefore, if the if the viscosity increases then this abrasive particles cannot move faster and neither the the breeze produced inside the cutting zone can be taken away faster nor thus abrasive particles after getting hit by the tool can move towards the work piece faster. And therefore, the material removal rate will slightly come down whereas with very low viscosity material medium we can see very good or very high material removal rate because of the reasons I have already stated.

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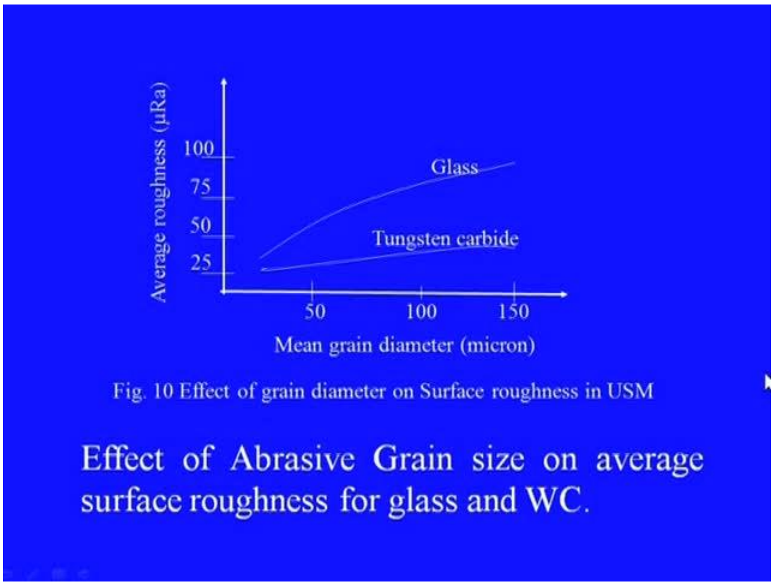

The next parameter is the mean grain diameter. This also already we have discussed, but let us see how how does this grain diameter parameter or the abrasive size, mean grain diameter is nothing but it indicates the size of the abrasives and therefore, as the size of the abrasive increases the average roughness obtained on the machined surface also increases. That means the surface quality becomes poor, this is quite obvious. So, higher grain size particles means it will cause cause higher indentation on the material and the debris produced or the fracture that will take place over the area will be much larger.

And therefore, the correspondingly the roughness of the surface that is been machined will be will be much higher that means that is indicative of poor surface. This particular characteristic is shown for tungsten carbide material and as on glass material. Glass is still brittle material, it is relatively more brittle then the tungsten carbide and therefore, it shows even poor surface finish with increasing diameter of the, diameter of the abrasive particles, but tungsten carbide been relatively relatively less brittle it shows little better or good response towards higher grain size even.

So, as as already we have discussed the surface finish in USM depends on the hardness of the work piece or the tool of the average diameter of the abrasive grain used. The process utilizes the plastic deformation of metal for the tool and the brittleness of the work piece. This combination works good for this particular process and as we have seen the grain size is a, in for as far as the surface finish is concerned higher grain size is is not good and as far as the material removal is concerned larger grain size is better or we can get better material removal rate.

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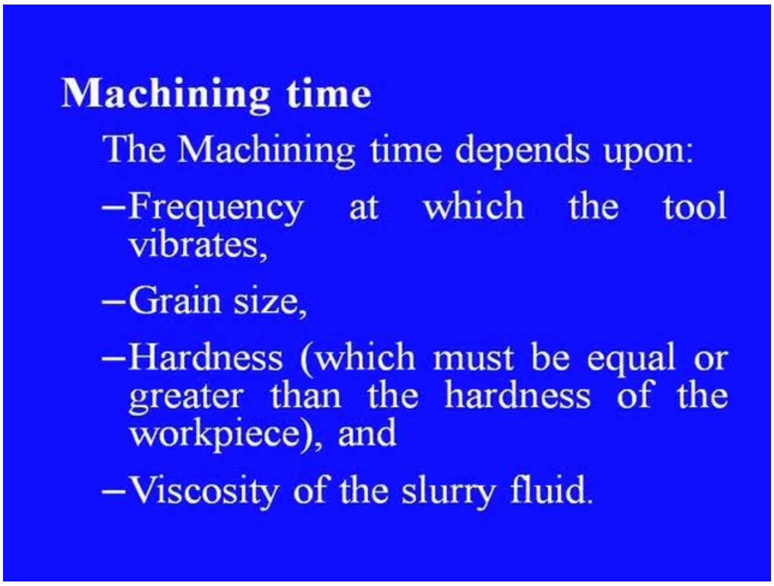

As far as the machining time is concerned it depends on the frequency at which the tool vibrates. Then on the grain size I have been already discussing about this grain size, importance of grain size as far as the MRR is concerned and as far as the surface finish is concerned. Then of course, the hardness which must be equal or greater than the hardness of the work piece and then the viscosity of the slurry fluid, regarding the viscosity also we have already discussed that lower viscosity generally gives rise to better material removal rate. Less viscous slurry gives faster machining as the, it can carry very easily the abrasives and the debris from the machining zone.

Considering the hardness the common grain materials are silicon carbide and boron carbide. These two materials are found to be very good as far as the hardness is concerned and as far as the effectiveness of these materials in machining is concerned. Now, let us have a quick look at the types of the ultrasonic machining.

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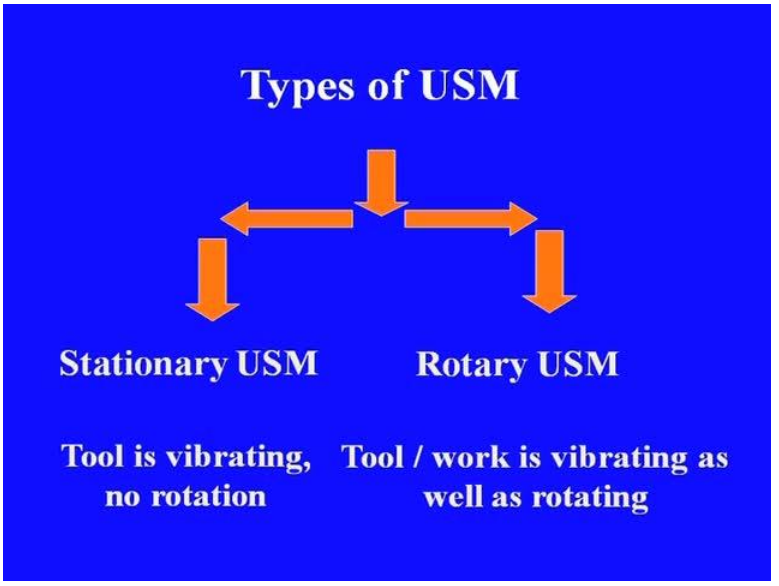

So, there are two types stationary USM in which tool is vibrating, but there is no rotation induced in it whereas the other is rotary USM known as rotary USM or R USM in which tool or work anyone can be vibrating as well as rotating also. In stationary ultrasonic machining this is a common process. So, this is, in most of the industrial applications we will find this stationary type of ultrasonic machining and this we have been discussing with reference to the stationary type only so far and in this only the tool vibrates while the work piece remains stationary and it is fed in the required direction. On the other hand let us see in the rotary ultrasonic machining.

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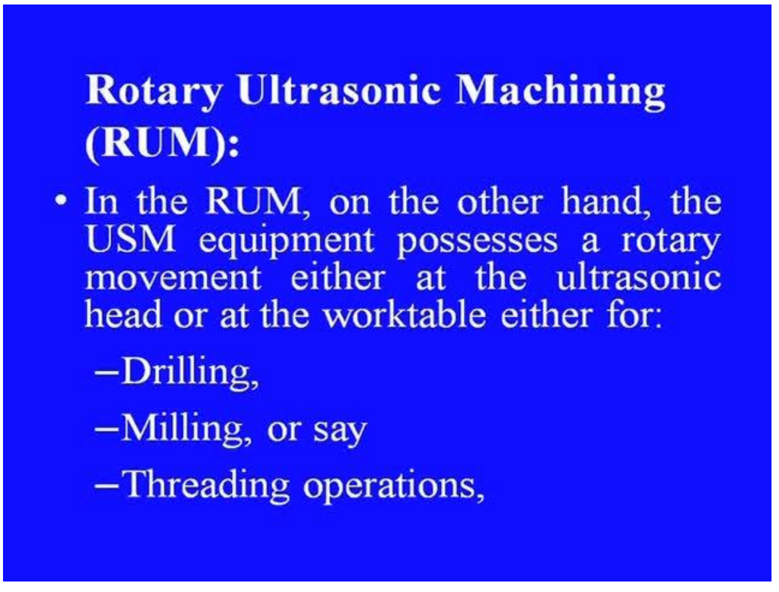

In rotary ultrasonic machining the USM equipment possesses a rotary movement either at the ultrasonic head or at the work table. So, this is used for mainly for drilling, milling or say threading operations. In rotary ultrasonic machines the combination of rotational motion and axial vibrations of the tool reduce the friction between the tool and the work piece material. This is the advantage of rotary ultrasonic machines and the spindle speed used in this is variable and it can be between anywhere between 0 to 8000 RPM.

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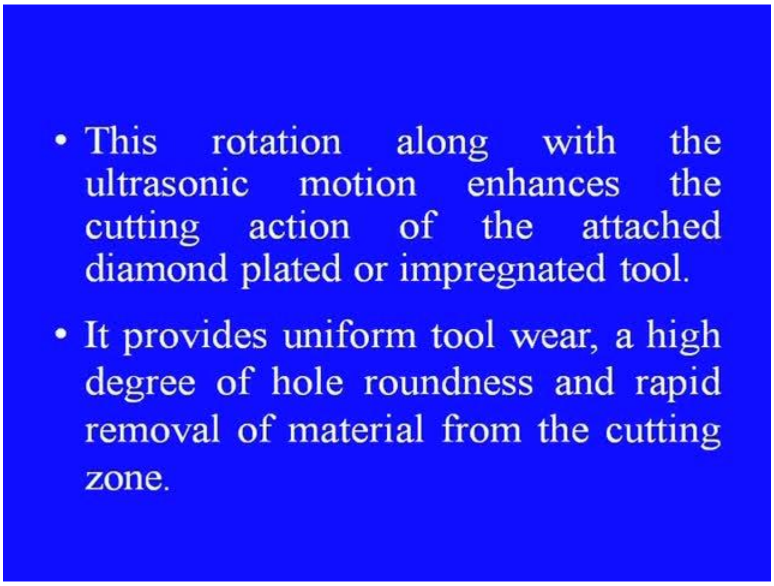

And this rotation along with the ultrasonic monition enhances the cutting action of the attached diamond plated or impregnated tool. It also provides uniform tool wear, a high degree of hole roundness and rapid removal of material from the cutting zone. Therefore, it is as good as far as the higher productivity is concerned and better finish is concerned.

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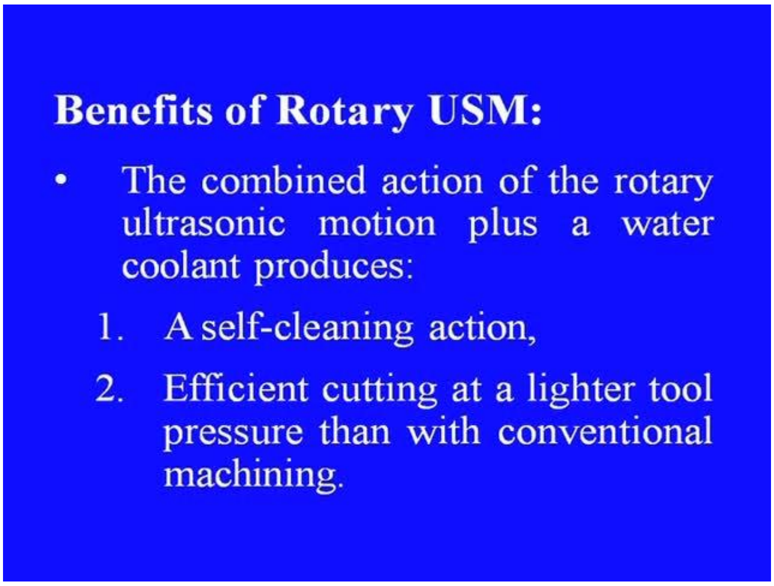

Let us see the benefits of the rotary USM. The combined action of rotary ultrasonic motion plus a water coolant produces a self cleaning action because of the tool is, tool head is rotating, it will be worst continuously, get worst continuously and then efficient cutting at a higher tool pressure than with conventional machining. Lighter tool pressure is advantageous for drilling small diameter holes, long deep holes and adjacent holes that are very close to one another, reduction in friction between the tool and the work piece that results in extending diamond tool life and reduces stresses caused by conventional diamond tool machining. So, these are the advantages of having rotary ultrasonic machining.

Now, in the end let us summarize what we have discussed in this particular session. We have seen the details of the ultrasonic machining process and working principle, the process parameters in details and their effect in various performance parameters like material removal rate as well as the surface finish or surface produced. We have seen also the types of USM, there are two types of USM rotary USM and the stationary USM. And we hope this session was very interesting and enjoyable.

Thank you.