Advanced Manufacturing Processes
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Module - 3
Advanced Machining Processes
Lecture - 5
Ultrasonic Machining Process (USM)

Welcome to this session on ultrasonic machining under the course advanced manufacturing processes. We have already covered two other processes, like abrasive jet machining process and what are jet machining process, and what are abrasive, what are jet machining processes? Under the category of mechanical processes in the advance manufacturing processes. Today, in the same series again in the mechanical energy based processes, we will try to discuss one more process named ultrasonic machining process. This process is very popular also known as USM and this is particularly useful and popular in the ceramics and glass industries. Let us move on to some details of this process.

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This process is a mechanical material removal best process, as I said already. This process is used to erode material in the form of fine holes and cavities in the hard or brittle work pieces. The process uses from tools vibrations of high frequency usually in the range of ultrasonic, something around 20 kilo hertz and above and as a suitable abrasive slurry, which contains one medium and one abrasive material like boron carbide, silicon carbide etcetera.

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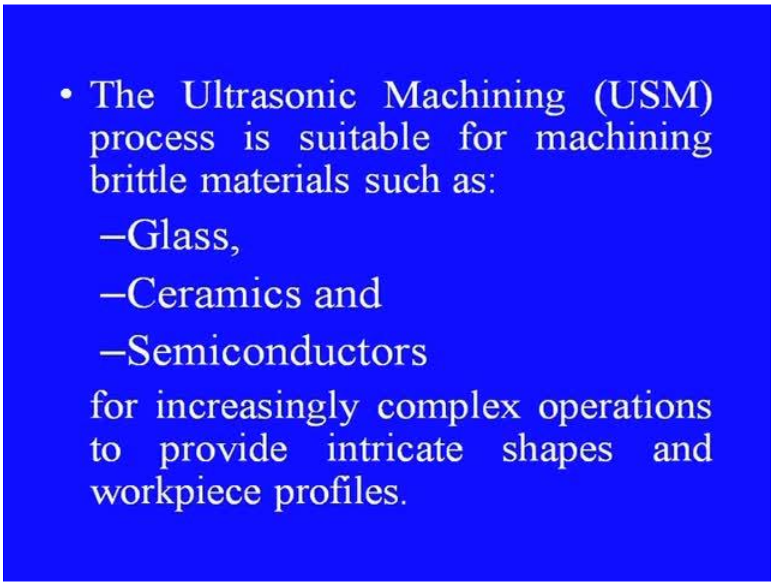

The ultrasonic machining also called USM is suitable for machining, glass, ceramics and semiconductors, for increasingly complex operations to provide intricate shapes and work piece profiles. This USM is a non thermal and non chemical process which creates no change in the chemical, physical or metallurgical properties of the work piece. It is therefore, widely used in the manufacturing of hard and brittle materials, which are commonly infeasible to machine by other nontraditional methods.

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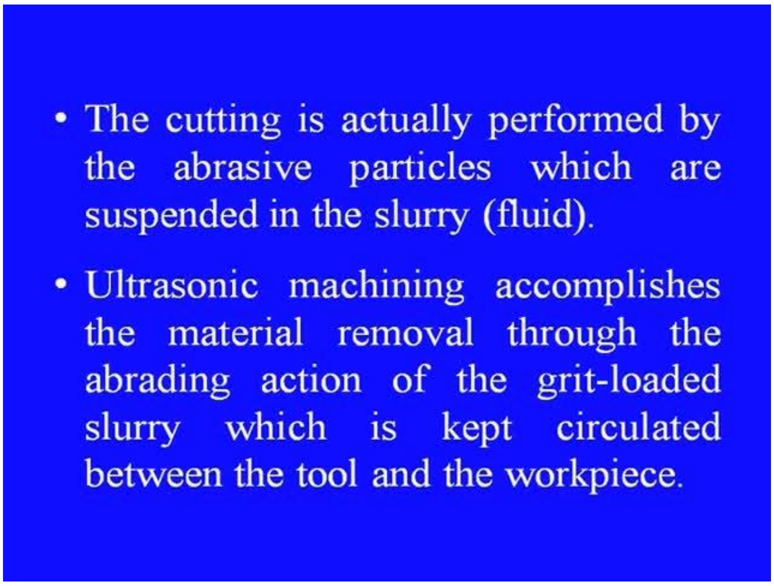

The cutting is actually performed by the abrasive particles which are suspended in the slurry. The ultrasonic machining accomplishes the material removal through abrading action of the greed loaded slurry, which is kept circulated between the tool and the work piece, this is schematically.

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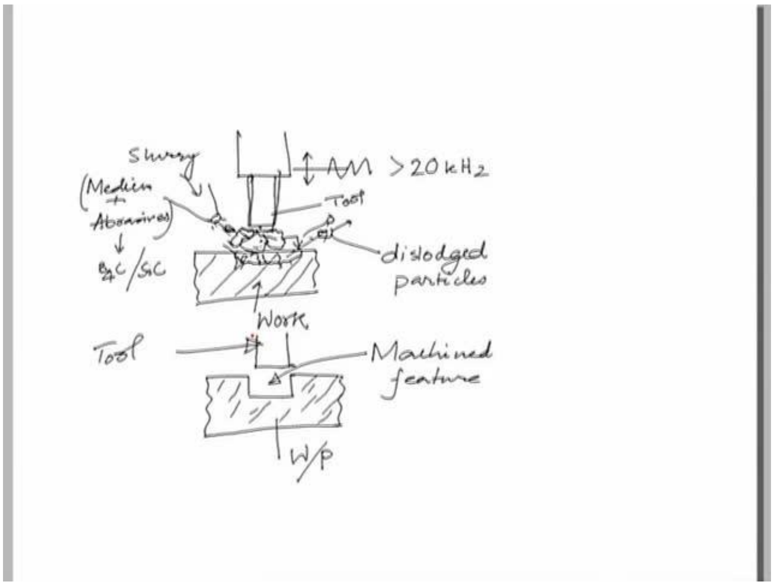

A tool is something like this and this is the target work piece or work surface to be machined. The slurry is made to flow through this, so this is slurry of which contains a medium plus abrasives. We will talk in details about this medium and this slurries later on. This abrasives can be boron carbide say B 4 C or can be silicon carbide and so on. Now, this tool is will be vibrating at ultrasonic frequency and this will be in access of or something like 20 kilo hertz or something like this. This slurry will be made to flow through this in this zone, therefore the abrasives will come in contact or in this zone something like this.

Then this tool will hit this abrasive particles, which will in turn hit this work surface and causes brittle fracture on this work piece surface. Then as a process as the process repeats, then this work piece surface gets fractured and the material from this will slowly get dislodged. Since, the slurry is flowing continuously this dislodged particles will be taken away by this. So, these are what we call dislodged particles, dislodged particles from the work piece.

So, this is the work part to be machined. Therefore, as this this is the shape of this work piece, so this will hit this particles on this corresponding area on this work piece. Therefore, this work piece will have an impression of the replica of this tool or the hitting feature. We are using in this case, so this will replicate this. This is the machined machined part or machined feature you can say on this work piece, this is the work piece and this is here the tool, and this is here the tool. So, this is the basic principle of ultrasonic machining process.

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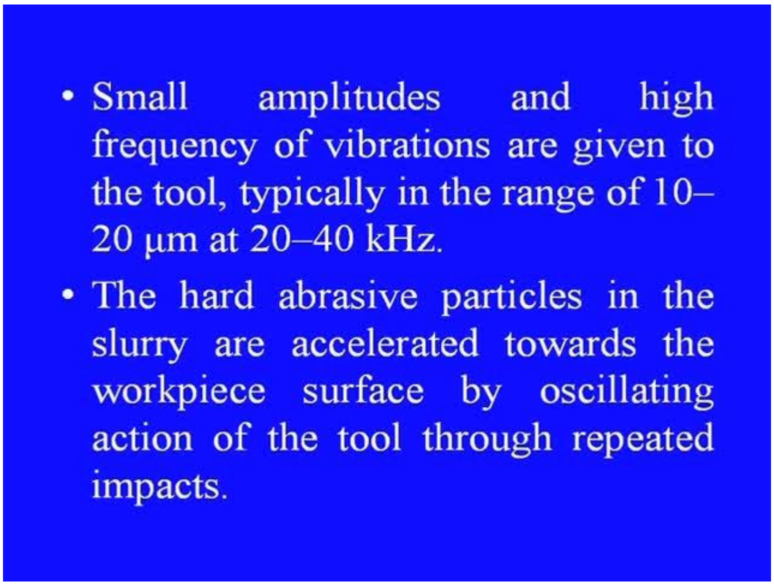

In this process small amplitude and high frequency of vibrations are given to the tool typically in the range of 10 to 20 micrometer at 20 to 40 kilo hertz, as I have already told. The hard abrasive particles in the slurry are accelerated towards the work piece surface by oscillating action of the tool, through the repeated impacts. The tool further machines a cavity of the cross section identical to its own, as I have already explained. A replica of the tool will be produced on the work piece surface. The material removal takes place in the form of fine grains by sear deformation.

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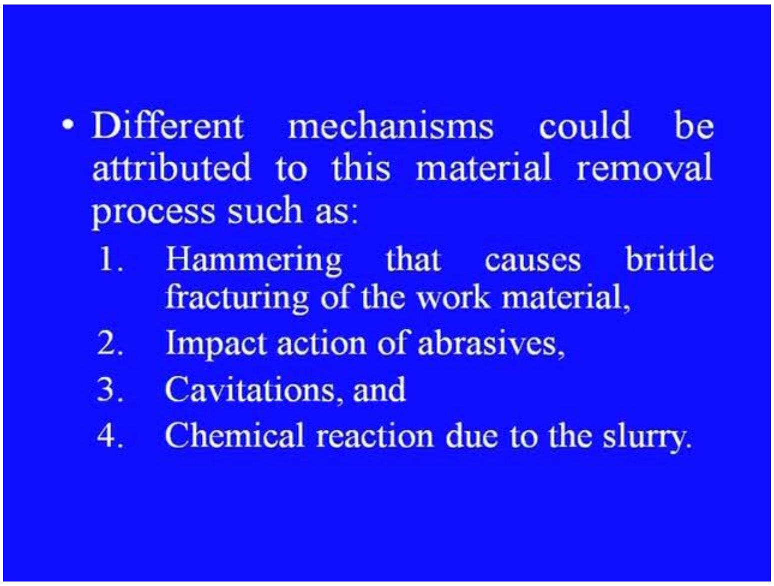

Different mechanisms could be attributed to this material removal process, there are mainly four mechanisms known mechanisms I should say. There may be some others, but not much evidence are evidences are being produced. However, some evidences are available as far as these four mechanism are concerned. Number one in this the hammering action, that causes brittle fracturing of the work material. Then number two is the impact action of the abrasives, that causes test concentration on the work piece surface and eventually the crack formations and dislostment of the material.

Then cavitations effect, which is the consequence of very rapid acceleration of the abrasive particles in the medium, that causes a pressure difference, which ultimately create a shock wave and that ultimately causes as the shock waves processed and the bobbles collapses, then material removal takes place on the work piece. Then the fourth action or mechanism of material removal is, the chemical reaction due to the slurry. As we have said there is the medium, this medium may contain some chemical essence, which may cause some chemical reactions on the surface of the work material.

Generally as we remove some material from the work surface, the newly developed surfaces will be nascence surfaces and they will be very, very prune to the chemical attacks. Therefore, it is possible that at these stage itself the chemical if present, in that slurry or in that medium might cause some reaction, which that nascence surface and which may eventually cause material removal in the form of corrosions or in the form of reaction materials from the work piece surface. So, these are the four basic mechanisms known mechanisms as for as the ultrasonic machining is concern.

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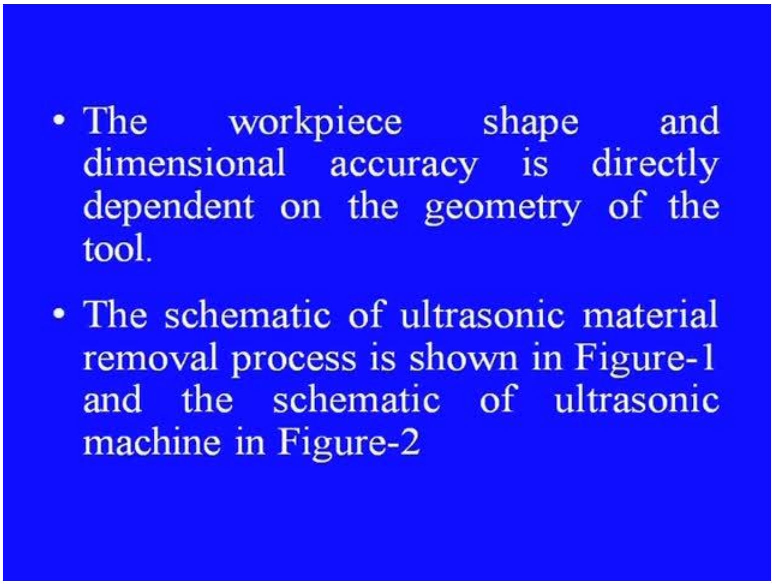

The work piece shape and the dimensional accuracy is directly depended on the geometry of the tool. The schematic of ultrasonic material removal process is shown in the figure.

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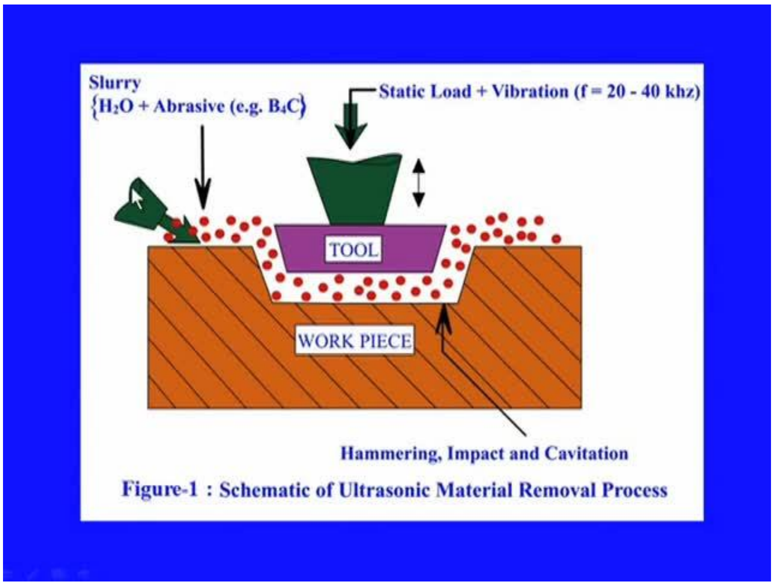

Figure-1 : Schematic of Ultrasonic Material Removal Process

So, here this is the basic figure of this ultrasonic machining process. So, here is the slurry is been fed or kept on circulated, this slurry contains one medium, which is very popularly water, H 2 O. On this some other abrasives like B 4 C boron carbide are being added and this concentration of this will vary depending on the application. Generally 30 percent or 40 percent of these abrasives will be added to this material and the sizes of these abrasives will also vary. It can be 1 micron and it can be up to 25 micron or 40 micron as well. Accordingly, the material removal or the cutting rate will also vary, depending on the size of these abrasive materials.

So, basically at this stage let us consider a mixture of this water plus abrasives are coming to this cutting zone, where the machining is to be needs to be carried out. This the tool, this the tool and this is the tool holding or the horn assembly, which will import ultrasonic movement to this tool and this will be vibrating as shown here, at some frequency predetermine frequency something around 20 kilo hertz or more. This will cause, these abrasive particles to accelerate towards this work piece at very high velocity. They will impact on this work surface with this energy energized particles will hit this work surface with very high energy, that is kinetic energy.

Therefore, this surface will get fractured by brittle fracture mechanism because of this. Moreover, this hammering action of this tool will take place on this surface because of this, movement of this tool. So, hammering an impact, as well as since this particles will be accelerated at very high speed as I said earlier, cavitations will also will take place because of this pressure difference, due to the acceleration of this particles in this media. Moreover, the chemical action may take place and these are the four mechanism that will take place in this.

Also added to this, while these particles will come out through this, this will abrade this side of this work pieces to some extent. That may also cause material removal on these sides and therefore, some sort of machining will take place on the sides of this work piece as well, in addition to the basic removal on this direct work surface. This is known as side cutting.

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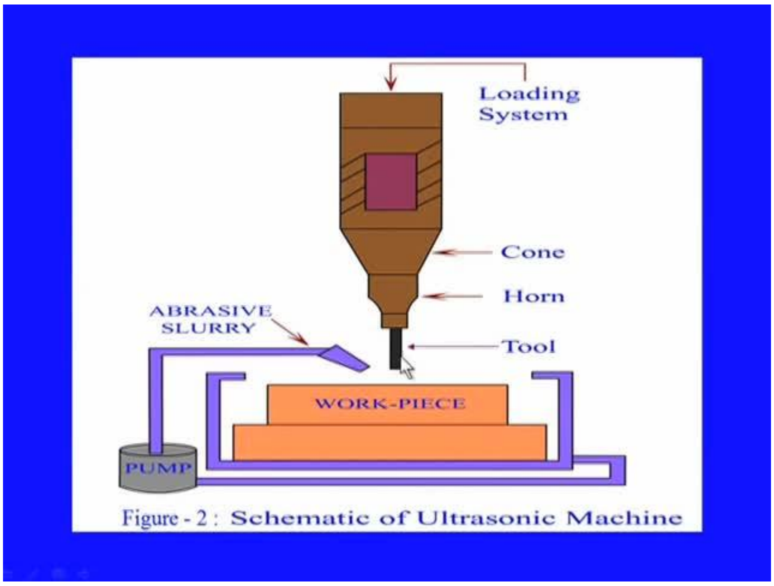

This is the set up as a whole, the ultrasonic set up. So, this is the loading system and this is the cone also known as concentrator or the horn assembly, which concentrates the ultrasonic vibrations, that is being generated here inside this. Some generation mechanisms are there devices are there and this ultrasonic frequency is being concentrated to the tool or given to the tool, tool head. This can take any shape as per the requirement. It can be square it can be cylindrical or and so on so forth.

The slurry will be kept on the flown through this slurry system, where there will be pump and filter systems etcetera, pump for keeping this slurry flown and filtering for filtering some of the particles, unwanted particles from this system. Of course, there will be some starrer kind of enhancements for keeping that slurry concentration uniform and work piece will be suitably clamped here and the machining will take place in this. So, this frequency of this oscillation and this load on this can be varied as per the applications.

Also I must mentioned here, that this configuration, this is a vertical configuration as per as this ultrasonic setup is concerned. However, the horizontal configuration is also possible in this ultrasonic machining case, in which the tool will will vibrate in this direction, rather than in this. Let us have a quick look at the historical developments of ultrasonic machining process.

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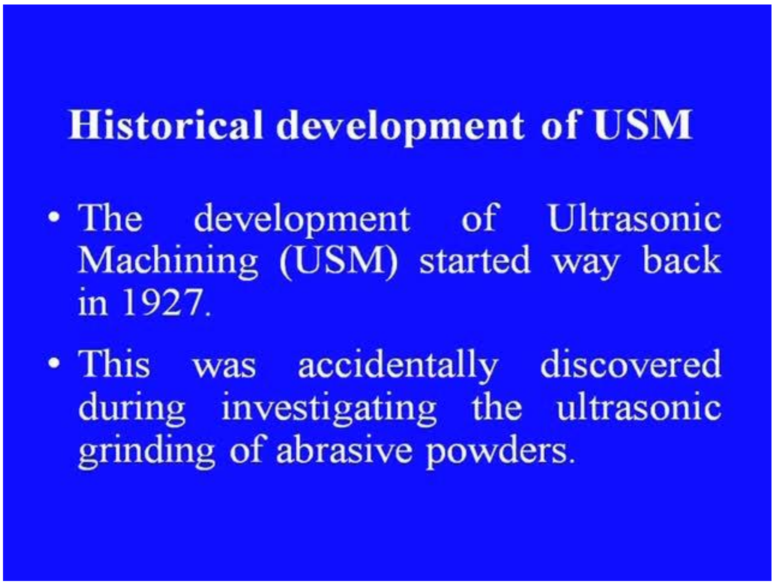

The development of this process USM started way back in 1927. However, this was accidentally discovered during investigating the ultrasonic grinding of abrasive powders. It was found at the surface of a container, which was holding the suspended abrasive, abrasives this integrated, as soon as the tip of an ultrasonically vibrating transducer was placed closed to it. The further interesting thing was, the shape of the cavity thus produced accurately reproduced the tip of the transducer. This was the first indication that, in through ultrasonic machining a tool shape can be reproduced on the job.

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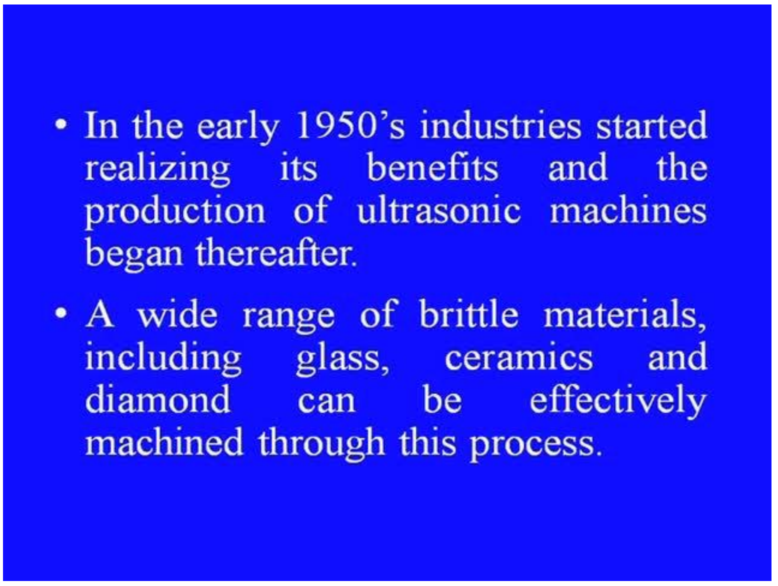

In the early 1950s industries started realizing its benefits and the production of ultrasonic machines began following that. A wide range of brittle materials including glass ceramics and diamond can be effectively machined through this process. Let us see the process, how it goes the ultrasonic processing is performed using a desirable tool along with the abrasive slurry as a media. The cutting tool oscillates at high frequencies, typically in the range of 20 to 40 kilo hertz. The shape of the tool corresponds to the shape requirements in the work piece, as I have already mentioned. It can take any shape.

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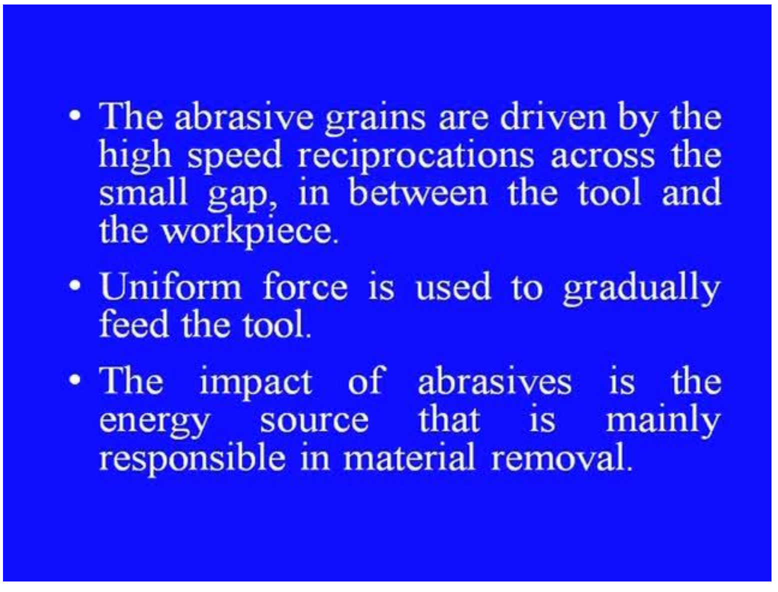

The abrasive grains are driven by the high speed reciprocations across the small gap in between the tool and the work piece, as already discussed. Uniform force is used to gradually feed the tool. The impact of the abrasive is the energy source that is mainly responsible in material removal. Due to the impact of abrasives, the material removal takes place in the form of small ware particles, which are carried away by the abrasives slurry. Due to the abrasive action of the particles casually ware of the tool occurs.

Thereby requiring the tool to be made of tough materials, tough materials means as we know, it will be able to absorb shock to some extent because this is works in the impact principle. Therefore, the tool as well receives some impact of the abrasive materials and it should be capable of absorbing this impact as well. Higher the stock absorption capacity, better will be the tool life. However, in the same time it should be able to deliver energy to the working particles as well. Let us have a look at the mechanisms of material removal in this process.

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Although the USM process is commercially used since many decades, the exact details of the mechanism leading to the removal of fine materials is yet to be understood well. The main mechanisms responsible for the material removal in ultrasonic machining are as follows.

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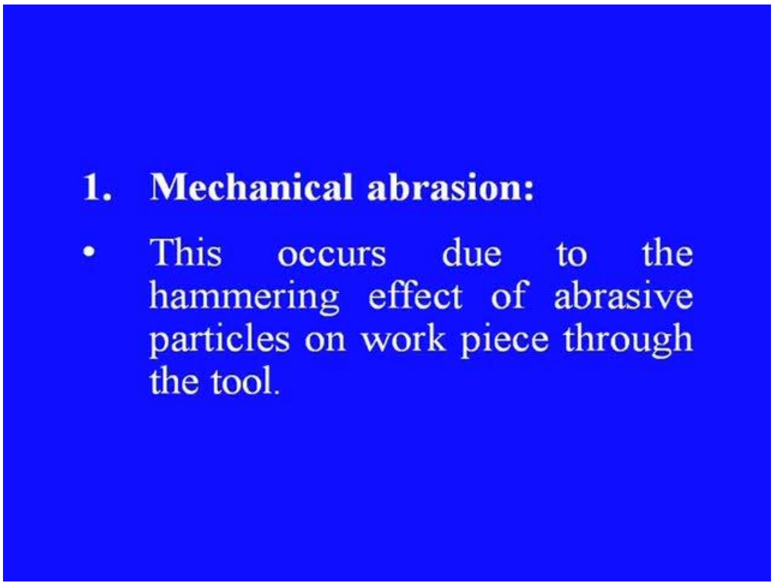

Number one is mechanical abrasion. This occurs due to the hammering effect of the abrasive particles on work piece through the tool.

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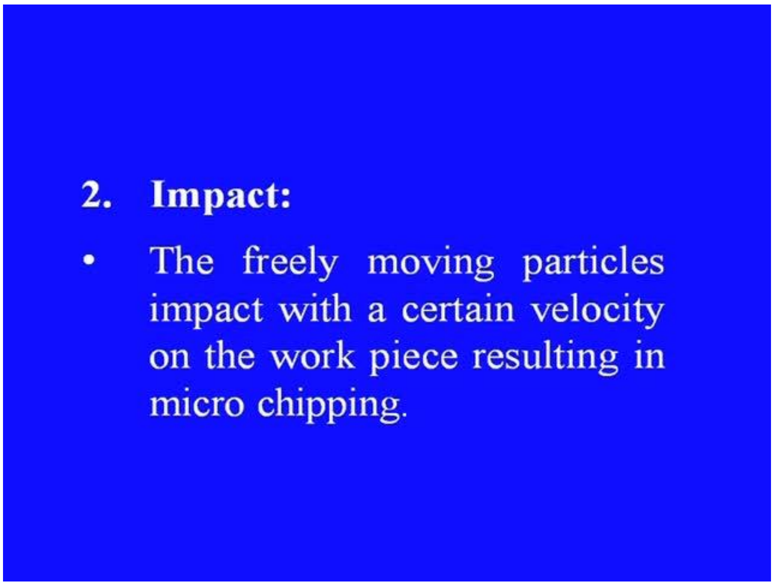

Number two is the impact. The freely moving particles impact with a certain velocity on the work piece, which results in micro chipping on the work piece surface.

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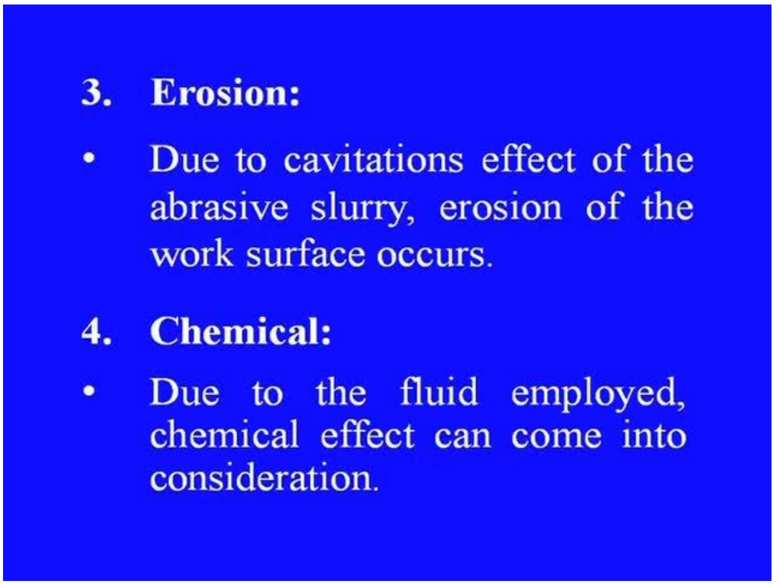

Number three is the erosion mechanism. This is due to the cavitations effect on the abrasive slurry which causes erosion of the work piece surface. Number four as I have indicated earlier, is the chemical action. Due to this the fluid in which some chemical essence are may be present the chemical effect can come into consideration. It has also been reported in the literature that among above mentioned mechanism the first two, that is hammering and mechanical abrasions and impact are primarily responsible for measure stock removal.

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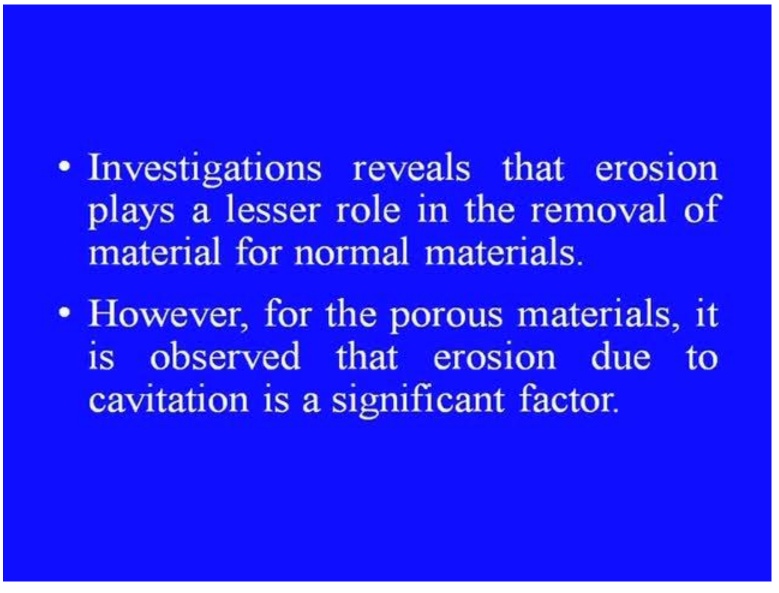

Investigations reveals that erosion plays a lesser role in the removal of material from normal materials. However for the porous materials, it is observed that erosion due to cavitations is a significant factor. Next, let us see the schematic presentation of an impact and possible mathematical interpretations of the impact due to a single grain, so this is where the abrasive is.

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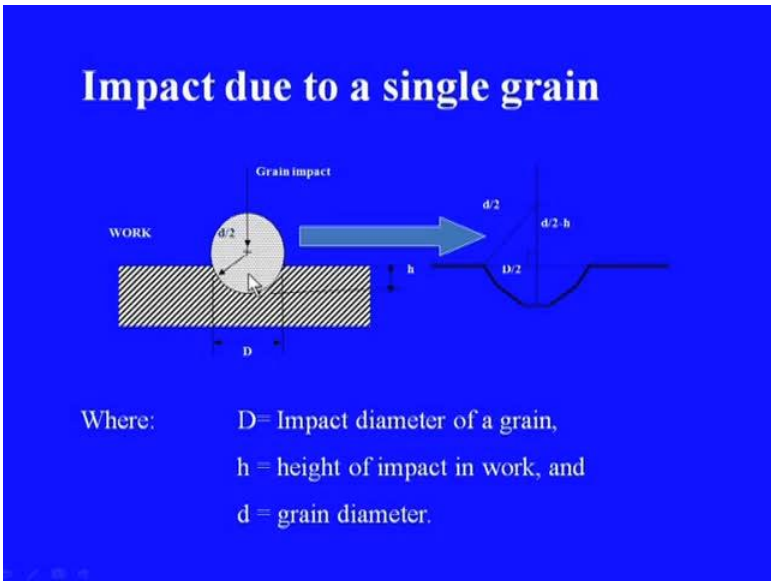

It is being hammered on this work piece. Suppose, this is being inserted or it is indenting the work piece by a distance something like h, the diameter of this particle is say d and the diameter here at at the impact point the maximum diameter is capital D. Then the geometry can be represented something like this, so this is the D by two distance and this is small d by 2 minus the height of the indentation, this is the height of the indentation.

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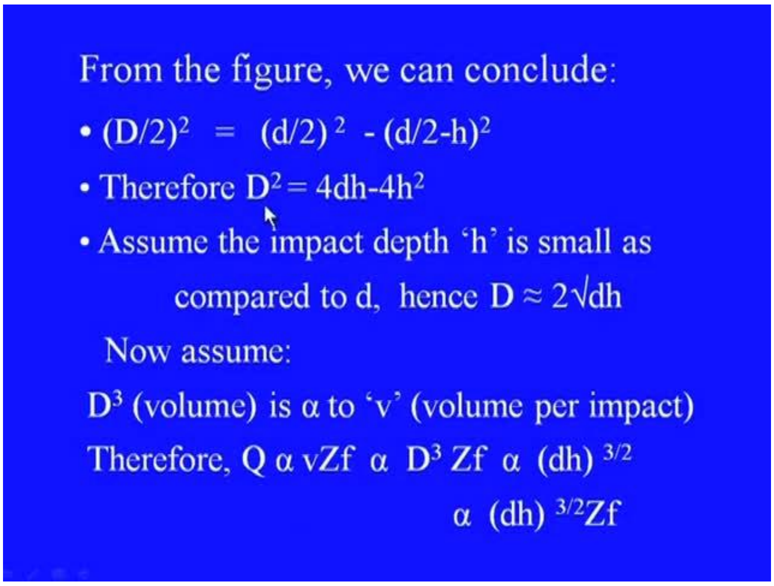

Now, using this trigonometrical relations of this geometry, then we can have we can arrive at something like this D by 2 square is equal to small d by 2 square minus d by 2 minus h whole square, which eventually gives D is, that is the diameter at which the abrasion abrasive is impacting or indenting is approximately equal to 2 under root d into h. Since, h is very small in comparison to the diameter of the particle, therefore this can be arrived at. Finally, it can be shown that material removal rate Q is proportional to the velocity, the volume per impact and then the frequency, frequency of this striking tool or the striking abrasives.

Now, let us look at the advantages major advantages of this processes, ultrasonic machining process. First of all there are no physical or chemical or thermal changes on the work piece and there is no physical contact. The micro structures reveal that there are also no structural changes as the stresses induced are too less. The cutting forces being low, work piece is unstressed undistorted and free from thermal defects.

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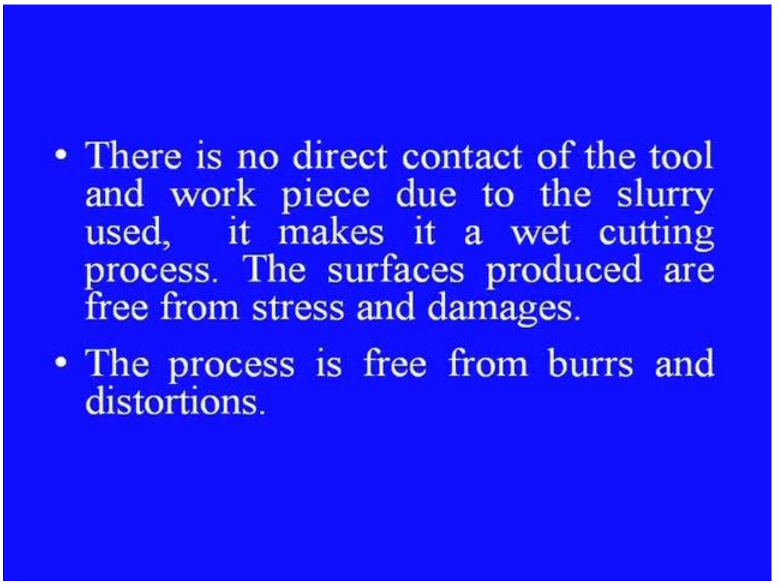

There is no direct contact of the tool and the work piece due to the slurry used and it makes it a wet cutting process the surfaces so produced are free from stress and damages. This is very significant as per as the process is concern or the produced part is concerned the process is free from burrs and distortions as well. Therefore, the process is suitable for any materials irrespective of electrical conductivity. However, the process is very much suitable for machining brittle materials. Essentially the process offers the good surface finish and structural integrity as well.

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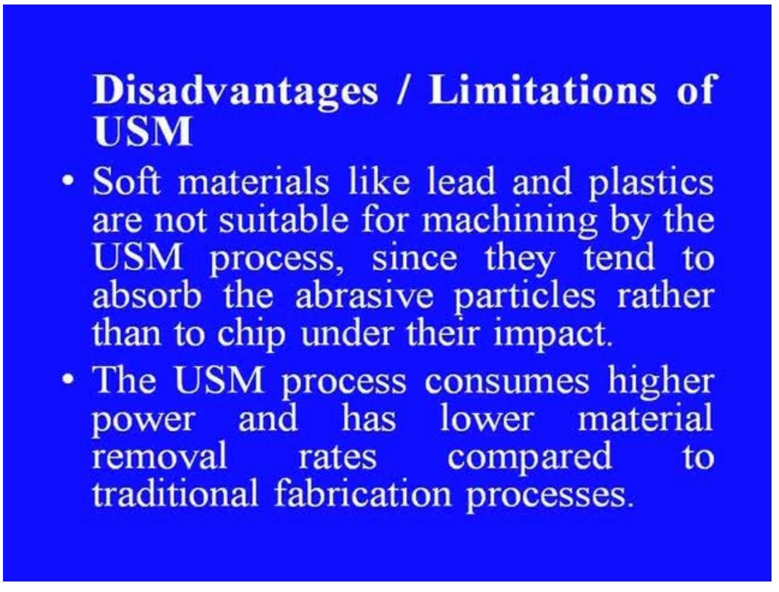

Let us look at the disadvantages or limitations of this process as well. Soft materials like lead and plastics are not suitable for machining by this process, since that they tend to absorb the abrasive particles rather than the chip under their impact. As I said already, this is the process where the impact energy is used and therefore if the material itself absorbs the impact energy, then there will not be any crack development.

Therefore, the failure of the material or the material final material removal will not take place. Therefore, this materials that absorbs the energy like soft materials are not good candidates for machining using this ultrasonic machining process. The ultrasonic machining process consumes higher power and has lower material removal rates as compare to traditional fabrication processes in this process.

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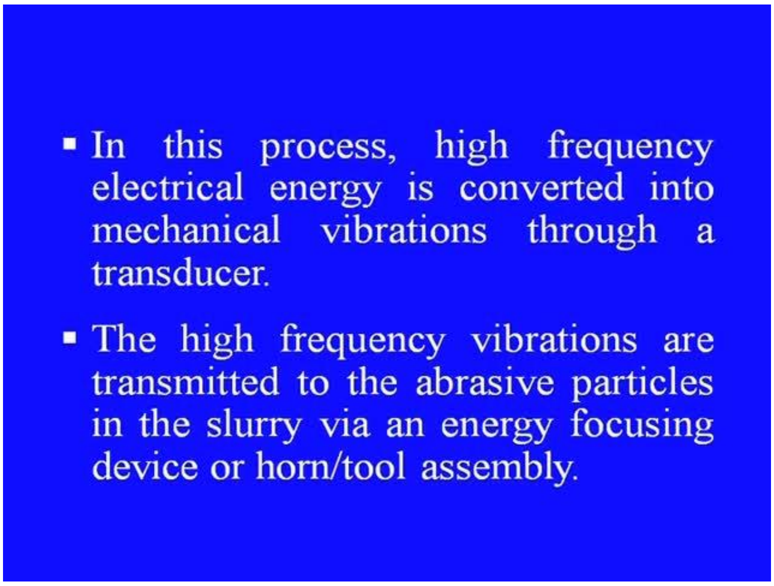

High frequency electrical energy is converted into mechanical vibrations through a transducer. The high frequency vibrations are transmitted to the abrasive particles in the slurry via an energy focusing device also called horn or tool assembly, as I have already indicated during the beginning of this session. Further point is the tool we are at in USM process is fast. Like this can be explained like this.

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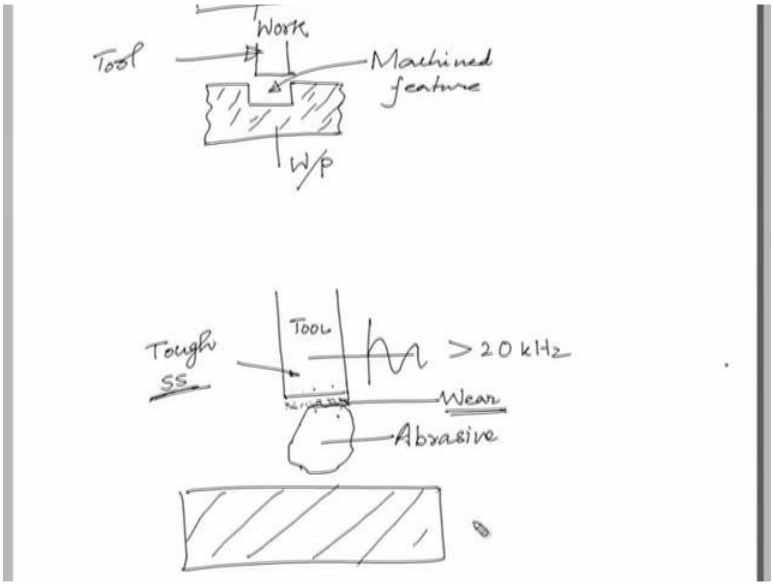

In this process as I told the tool will hit the abrasive particles something like this and this abrasive particle will in turn hit this work surface. Now, as this tool comes in contact with this abrasive particle, therefore there will be an impact on this, on the part of this tool as well. So, this is the tool and this is the abrasive. Therefore, what happens, this tool also under goes some sort of stresses under the impact of this and we should remember this is moving at very high frequency, which is something around 20 kilo hertz or more.

Therefore, this tool end is also susceptible for wear during the process. In fact it gets one out very frequently, while working with this process. Therefore, this tool needs to be changed very frequently, in order to overcome this process generally this tool material is generally little tough materials are selected. Generally stainless steel are good work materials in this case and it has got considerably better work life otherwise some other materials also chosen.

As the USM process process continue process continues the lateral ware of the tool increases generally and it tends to make the holes tapered, this is also another problem as for as this USM is concern. Soft corners of the tool get rounded of, thereby requiring the tool replacement essential for producing accurate blind holes. The accuracy of the machine surface gets lost, due to setting up of strong lateral vibrations. So, this can be again explained like this.

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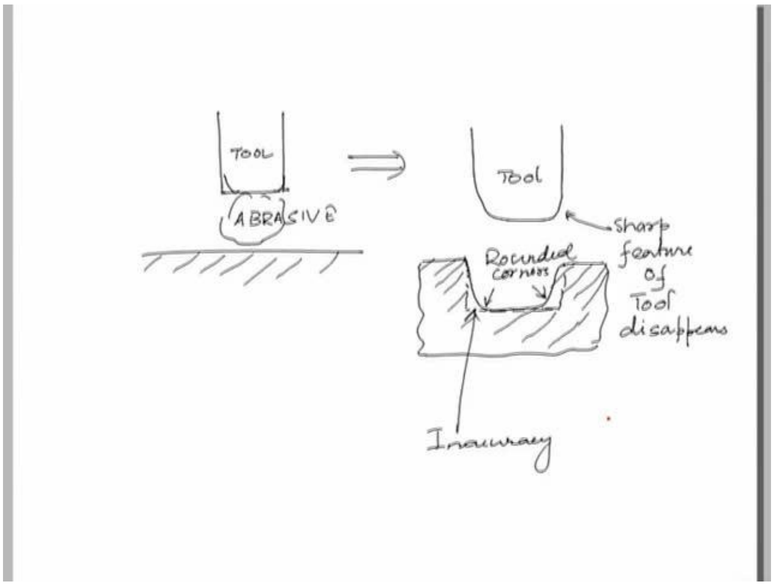

Because of the continuous impact of this tool, so this tool and this is say abrasive abrasive and this is work piece surface. After sometime what happens, this sharp corners of this tool gets rounded of something like this and the resulting tool becomes something like this. So, sharp features sharp features of the tool, of tool disappears here, disappears and also this is again reflected on the work piece as well. Since, this replica is produced therefore, the the corresponding hole to be produced will be will be something like this.

Therefore, a rounded corner or a radius rounded corners will appear instead of sharp corners, which ideally should have been something like this. So, this is this is this is a kind of kind of inaccuracy associated with this process. This accuracies accessed of the tool and the horn, which are braised together are not properly aligned, which the transducer access. This might cause the lateral lateral movement of the tool end also. That might also give rise to the inaccuracy of the feature or the hole to be produced or the cut to be produced, in such a case tool need to be redesigned.

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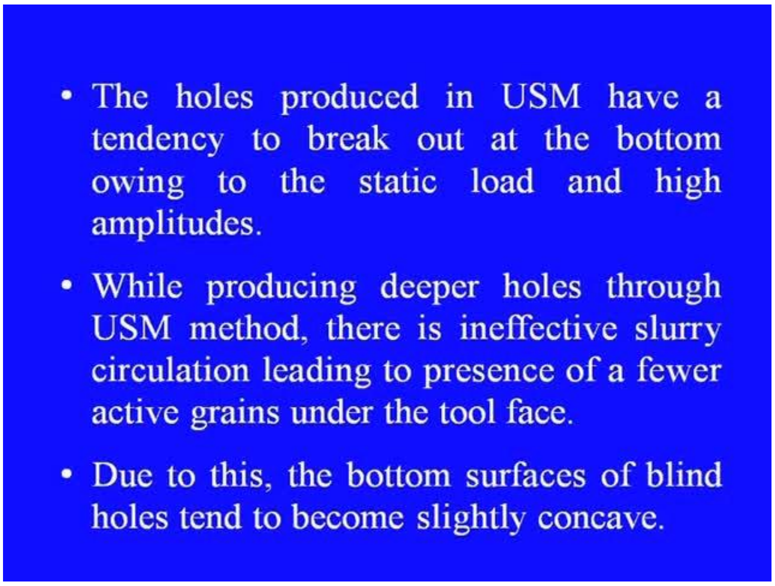

The holes produced in ultrasonic machining have a tendency to break out at the bottom while the static load and high amplitude is used. While producing deeper holes through this method, there is ineffective slurry circulation leading to presence of the fewer active grains under the tool face. Due to this the bottom surface of the blind holes tend to become slightly concave. As I have already shown, there will be radius formation at the bottom of the hole. That is, that means we can conclude the ineffective cutting at the bottom of the hole, in case of the hole depth is more. Let us quickly look at the working principles of this process.

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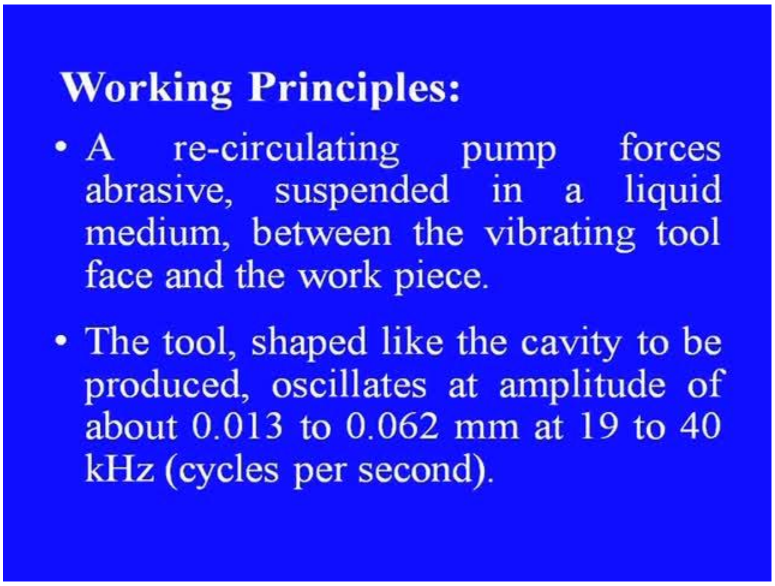

A re-circulating pump forces abrasive suspended in a liquid medium between the vibrating tool face and work piece. Then the tool shaped like the cavity to be produced oscillates at an amplitude about 0.013 to 0.062 millimeter at 19 to 40 kilo hertz. The tool vibrates abrasive grains against the surface of the work piece, thus removing the material. The abrasive particles strike the work piece at 150000 times their own weight. These turning abrasive particles chip of microscopic flex and grind a counter part of the tool surface. Let us look at the ultrasonic machine setup.

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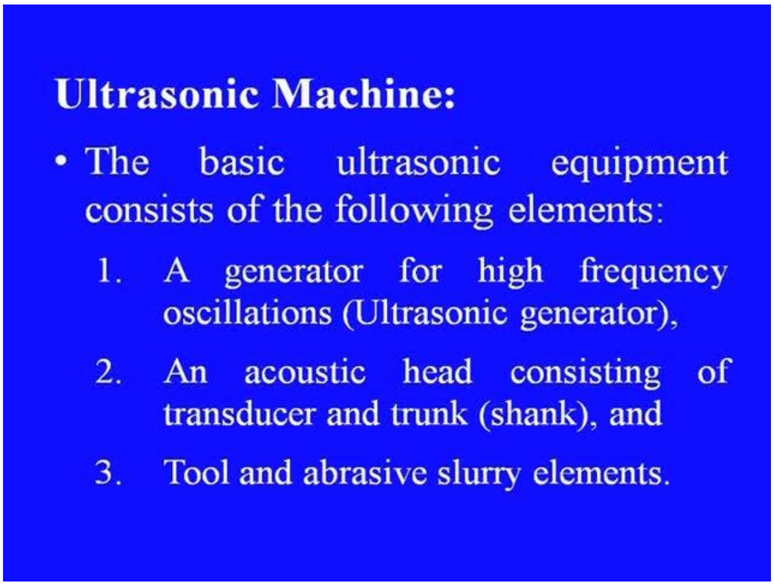

The basic ultrasonic equipment consists of, a generator for high frequency oscillations. Then an acoustic head, consisting of transducer and horn also know as shank or trunk, then tool and abrasive slurry elements. This is shown in the schematic like this.

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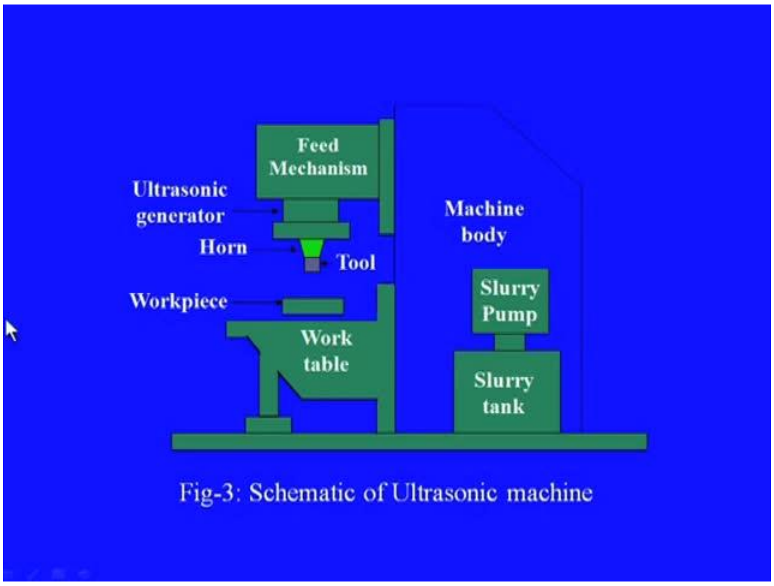

Fig-3: Schematic of Ultrasonic machine

So, this is the overall structure of the of the setup and this is the work table on which the work work piece is been clamped and this is working head also as the tool. This is where the ultrasonic generating facilities will be located and ultrasonic frequencies will be transmitted through the horn assembly or the clamping device to this tool. So, ultimately we will be observing the mechanical oscillations or displacements of this tool head at this point.

This height of this tool head with respect to the work table is adjustable through some mechanisms here. This will be adjusted as per the requirement of the work piece. Another important component is the slurry circulation system, in which the abrasive and the media, that is water will be made and will be kept on circulated and kept on stirred and flown to this zone through some host enhancement or tubing enhancement. The flow rate can be controlled at this stage, flow rate of the slurry flowing through this can be controlled very well.

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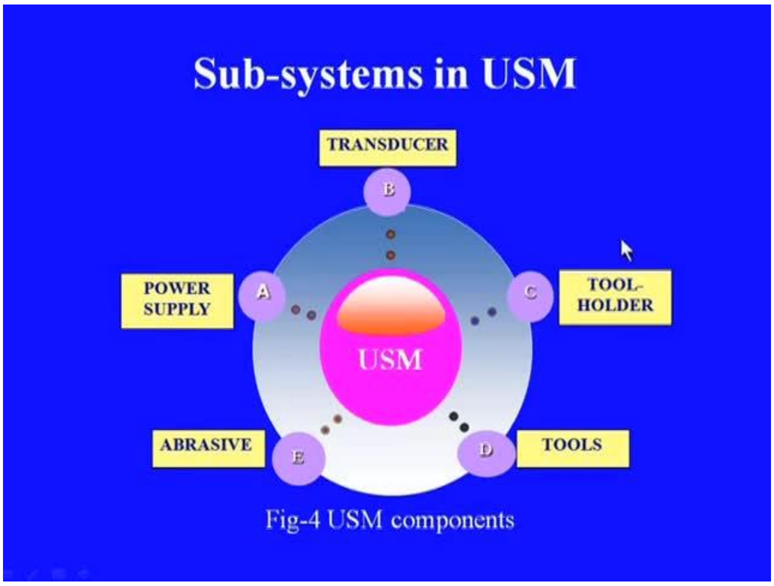

So, these are the main subsystems effecting this ultrasonic machining system. The transducer, which produces, which is responsible for producing the ultrasonic frequency. The tool holder, which is responsible for giving a reseed clamping of the tool and transmitting the the frequency from the transducer to the tool head. Then the tools, the tool itself, which will be responsible for producing the accurate feature on the work piece. The tool will be as per the requirement of the job.

Then the abrasives, which will be basically responsible for making contact with the work piece, which will hit the work piece and remove the material from the work work piece. The power supply system to the entire system for producing ultrasonic frequency for keeping the slurry system flowing and so on. These are the main basic subsystems in an ultrasonic machining system, as I said the power supply of the machine comprises of the high frequency oscillating generator.

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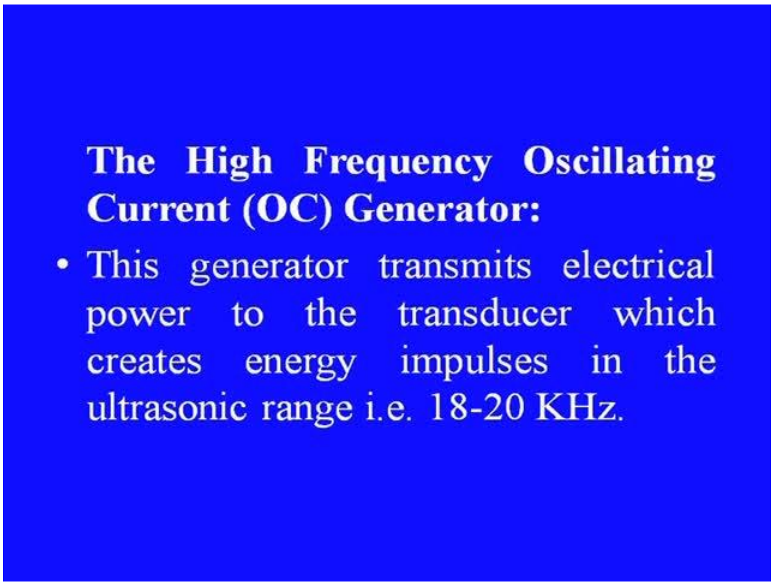

This generator is responsible for transmitting electrical power to the transducer, which creates energy impulses in the ultrasonic range. That is sometime starting from 18 kilo hertz onwards. The energy pluses are then converted into mechanical vibrations. The primary function of the transducer is to convert these electrical impulses into vertical and two dimensional strokes. Sometimes it can be horizontal as well, depending on the configuration of the machine.

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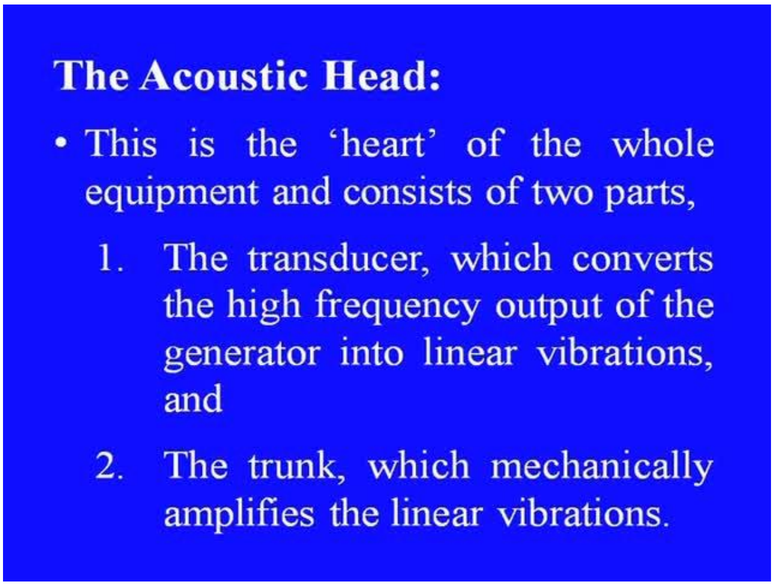

The acoustic head is considered as the heart of the whole equipment and this mainly consists of two parts. The transducer, which converts the high frequency output of the generator into linear vibrations, the number two the horn or the trunk, which mechanically amplifies the linear vibrations. The transducer, ultrasonic transducer, so here this responsible for producing the ultrasonic vibrations and is driven by the signal generator, which gets further power by an amplifier. The ultrasonic machining transducer works on the following principles.

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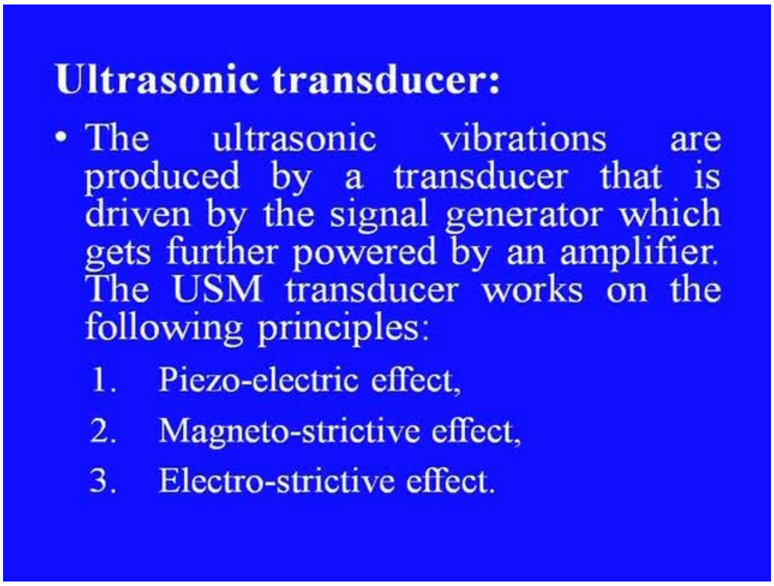

Piezoelectric effect, magneto-strictive effect and electro-strictive effect. The function of an ultrasonic transducer is to convert the high frequency electrical impulses from the oscillator into mechanical vibrations. The periodicity of these vibrations periodically shortens and lanterns. For low power applications these are electric transducer are used whereas for high power applications magneto-strictive transducers are preferred.

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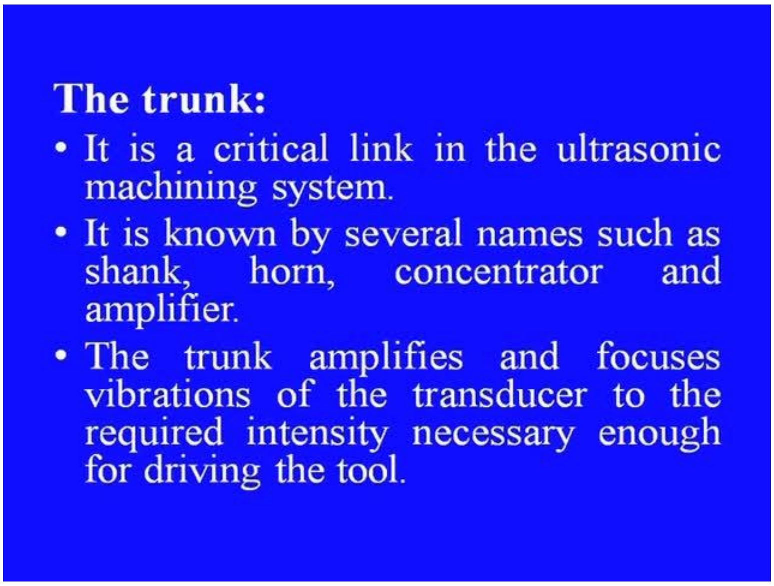

Next let us see the trunk assembly, it is also a critical link in the ultrasonic machining system. This is known by several names such as shank, horn, concentrator and amplifier as well. The trunk amplifies and focuses vibration of the transducer to require the intensity, necessary enough for driving the tool. The increase in amplitude of vibrations at the tool end is obtained by reducing the cross section of the trunk.

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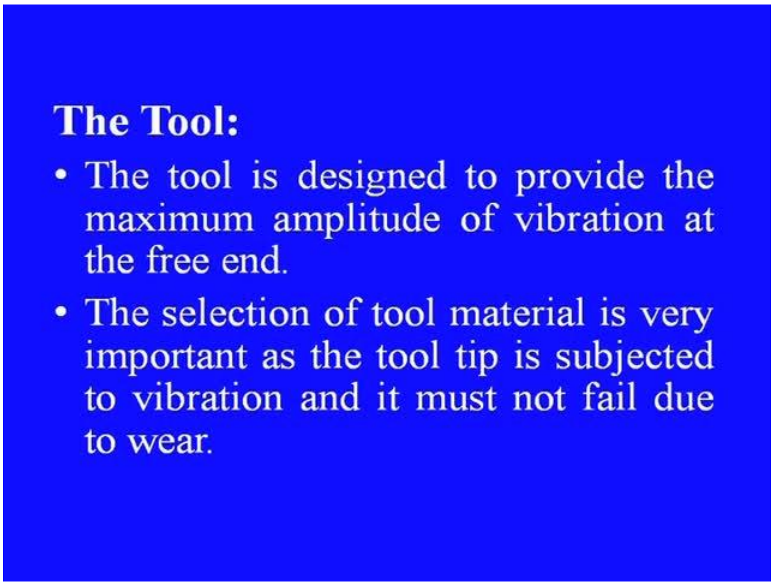

Now, let us see the tool. The tools is designed to provide the maximum amplitude of vibration at the free end, the selection of the tool material very very critical as I have already indicated. The tool tip is subjected to vibration and it must not fail due to severe wear, it has to undergo during the machining process. The commonly used tool materials are brass, high speed steel, mild steel, silver, stainless steel, tungsten carbide and monal metal. The tool is attached to the trunk or the horn by silver brazing process or by hertz (( )). At times it is fasten or the screwed to the trunk also.

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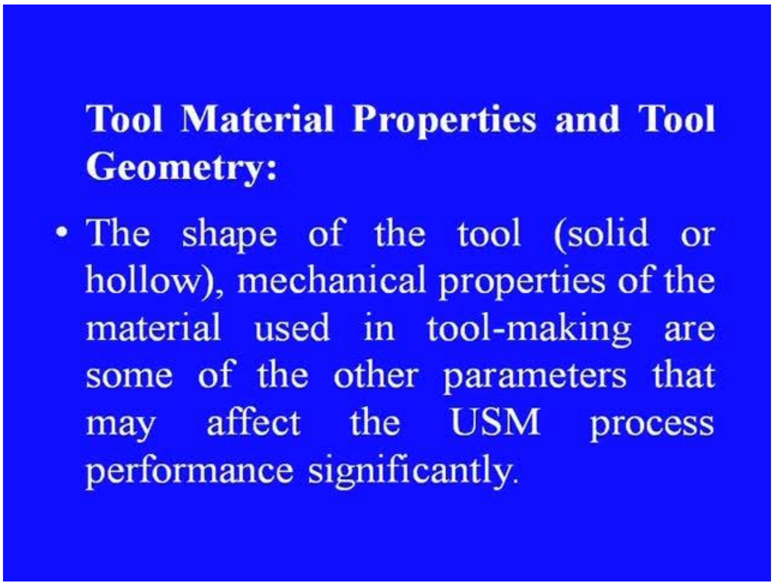

The tool material properties and tool geometry. The shape of the tool solid or hallow, mechanical properties of the material used in tool marking are some of the other parameters that may affect the ultrasonic process performance significantly. As we have indicated already, the tool material should be tough in nature. Now, quickly let us have a look at the applications of this process, ultrasonic machining process.

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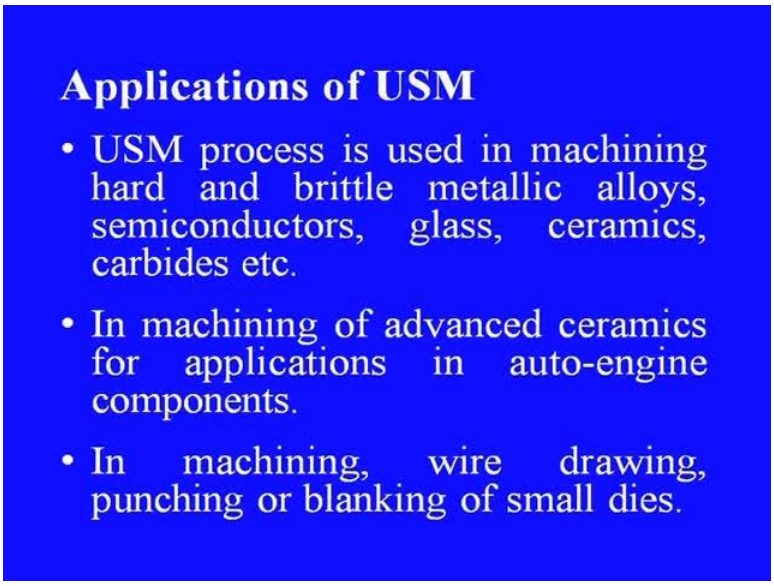

This is used in machining hard and brittle metallic alloys semiconductors glass ceramics carbides etcetera. Basically as we have already indicated this is a process directed for glass and other harden brittle materials. The machining of advance ceramics for applications in auto engine components this is used. The process is also used in machining wire drawing, punching or blanking of small dies. The process is also used in machining ceramic substrates for drilling holes, in borrow silicate glass for sensors used in electronic industries.

Drilling small holes in helicopter power transmission sharps and gears, this process is used. Now, let us have a very brief summary of what we have discussed today. The ultrasonic machining process is basically a non thermal and non chemical process, used for machining hard and brittle materials. It can be used for drilling channeling profiling and micro machining features, which are otherwise difficult to generate with traditional machining processes on hard and brittle materials.

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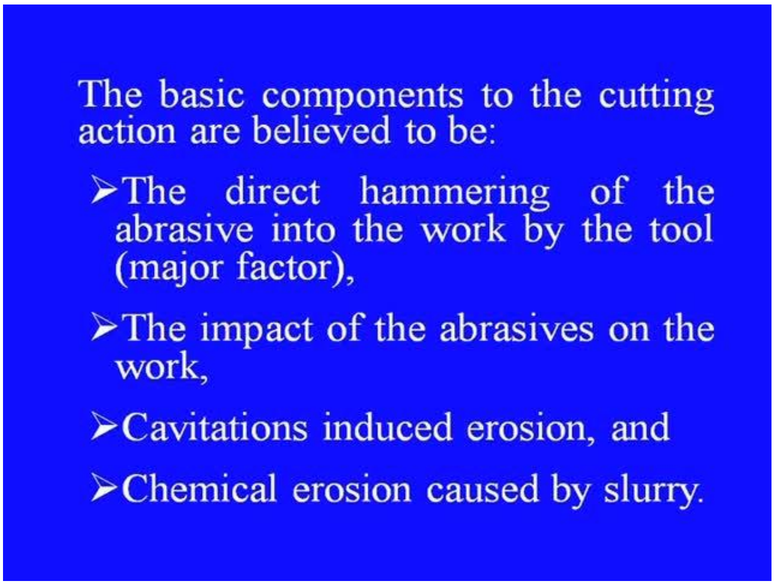

The basic components to the cutting actions are believed to be the direct hammering of the abrasive into the work by the tool, which is a major factor responsible for material removal. Next is the impact of the abrasive on the work and other two minor mechanisms or the factors are cavitations. Cavitation induce the erosion and then chemical erosion caused by the slurry.

So, with this we have discussed the development of this USM process in this session. Then the basic process of this ultrasonic machining, it is working, principles and then applications, the advantages and limitation of this process. We hope this session was interesting and fruitful.

Thank you.