Advanced Manufacturing Processes
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Module - 3
Advanced Machining Processes
Lecture - 7
Micro USM and Advances in USM

Welcome to this one more session on ultrasonic machining under the course advanced manufacturing processes. In the previous sessions, we have discussed about the basics of ultrasonic machining process, principles of working, mechanisms of material removal in ultrasonic machining, its various features, different measures of systems of the setup, then parametric affects on its performance. Particularly, as far as the material removal rate is concerned and as far as the surface quality is concerned, and of course different types of USM.

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In this session, we will try to explore the following: The advancements in ultrasonic machining, namely micro USM and its features advances and other research issues, then potential applications and of course future trends of this important technology. Today, it has been recognized that the miniaturization has been one of the major themes in manufacturing. Miniaturized products are in strong demand, because of their unique advantages, such as less space requirement, less energy and material consumption easiness in carrying and or handling and can be cheaper as well.

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The growth of micro electro mechanical systems, as we all all know it in a better terms as MEMS, as well as NEMS. Nano electro mechanical systems and the related research in different industries such as electronics, optics, medical, biotechnology, automotive, avionics and communications are largely attributed to micro components.

Miniaturization poses multiple challenges and demands and it is it needs continuous innovations in manufacturing. So, it is a challenge for the manufacturing industry, how to cope up with this increasing demand for miniaturization, which we cannot deny. Perhaps, industrial applications for complex three dimensional systems in micro scale are still limited by materials, geometrical limits and fabrication process costs and time. We may ask for miniaturized product, but how to get it realized that is a very big issue.

In particular the materials, different materials, as far as the product requirement is concerned the material can be different or there can be a strict guidelines for choosing that particular material. However, as far as the manufacturability is concerned that dimension, that manufacturing in that range may not be possible, in that particular material. So, these are some of the operating difficulties that has to be overcome by the manufacturing engineers.

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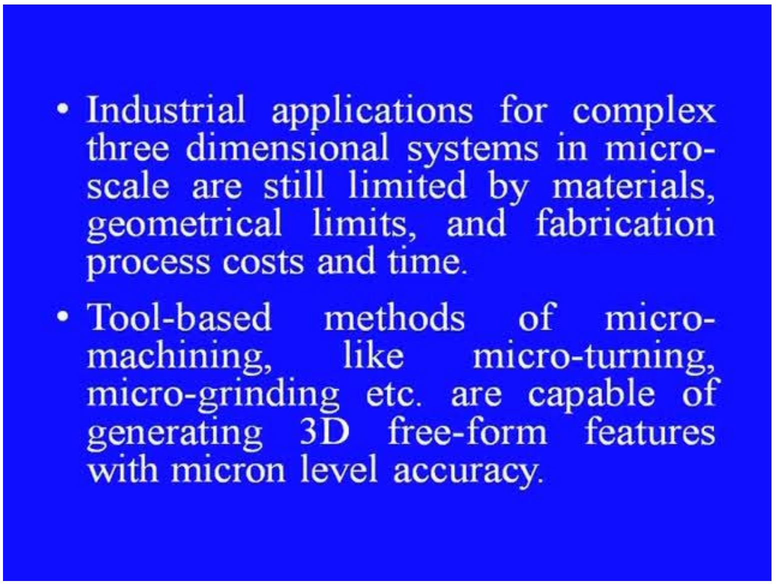

Tool based methods of micro machining like micro turning, micro grinding etcetera are capable of generating 3D free form features with micron level accuracy. There are certain other techniques, micro machining techniques like liga etcetera, but these processes are basically 2D processes. 3D features are very difficult to produce by these processes, whereas these processes like micro turning or micro grinding etcetera. In micro level these are two cores to be realized.

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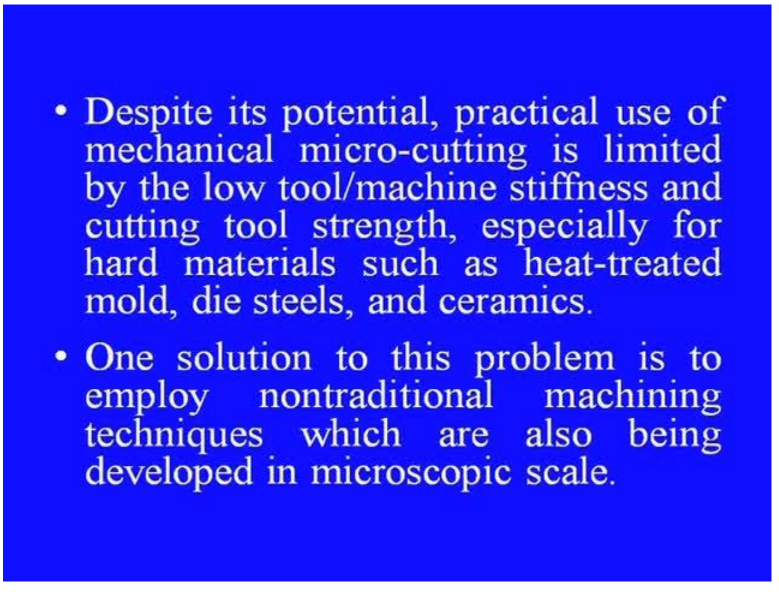

Despite its potential practical use of mechanical micro cutting is limited by the low tool or machine stiffness and cutting tool strength. Especially for hard materials such as heat-treated mold, die steels and ceramics. So, where is the solution then? One solution to this problem could be to employ nontraditional machining techniques, which are also being developed in microscopic scale. This is the context in which we are going to discuss, this particular session like towards implementing this ultrasonic micro machining technique, at a micro domain.

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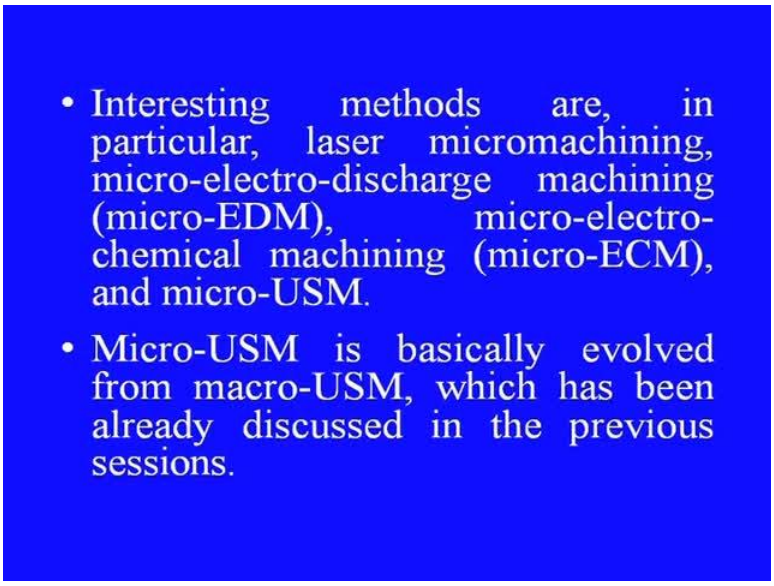

Interesting methods are in particular laser micro machining, micro electro discharge machining also called micro EDM, micro electro chemical machining also called micro ECM and micro USM can be thought of using for these particular purposes. Micro USM that is, nothing but at micro level ultrasonic machining is basically evolved from macro USM, what we usually known as USM or normal USM, which has been already discussed in details in the last two sessions.

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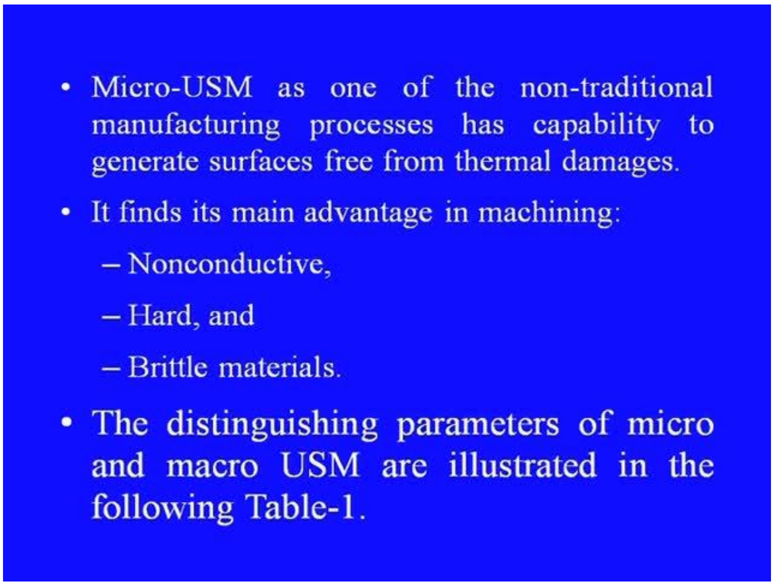

Micro USM as one of the nontraditional manufacturing processes has capability to generate surfaces free from thermal damages. This is one of the biggest advantages in applying this ultrasonic micro machining process. It finds its main advantage in machining non conductive hard and brittle materials, as we have already discussed with respect to the normal USM. The distinguishing parameters of micro and macro USM are illustrated in this following table, let us see where do we differ.

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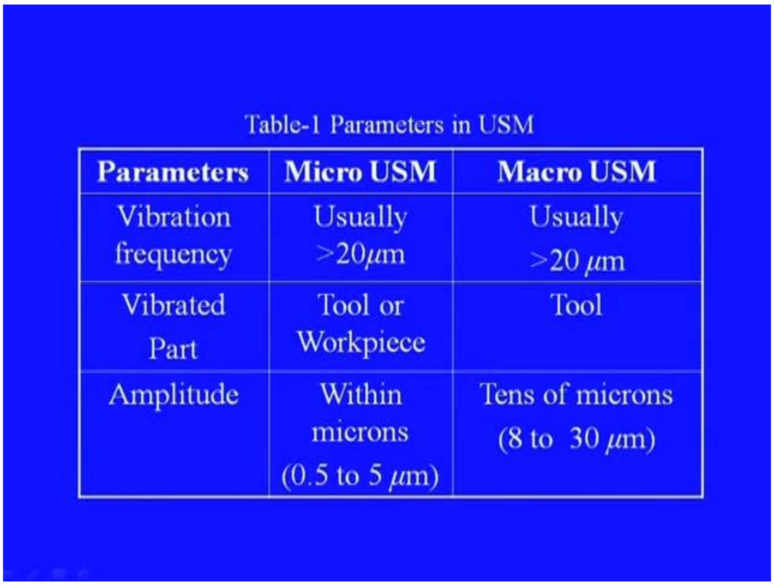

Table-1 Parameters in USM

Parameters	Micro USM	Macro USM
Vibration frequency	Usually >20μm	Usually >20 μm
Vibrated Part	Tool or Workpiece	Tool
Amplitude	Within microns (0.5 to 5 μm)	Tens of microns (8 to 30 μm)

As far as the micro USM and macro USM is concerned, the vibration frequency is in both the cases in the ultrasonic range that is greater than 20, 20 kilo hertz. It should be 20 kilo hertz and then vibrated part can be either tool or work-piece, in case of micro USM. But in macro USM generally the tool is vibrated. In micro USM there are reports few reports in which, researchers have studied imparting the vibrations to the work-piece as well and they have got good response with this particular technique.

Therefore, in as far as the vibration is concerned, both can be subjected to this ultrasonic vibration in case of micro USM. As far as the amplitude of vibration is concerned, in micro USM it is generally limited to 5 micro meter amplitude, it can range from point 5 micrometer. Whereas, in case of macro USM it is in between 8 to 30 micro meter depending on the application and so on and it can slightly vary lower than this or higher than this as well. But in general, if we see the range, this is much higher than that of the range used in micro USM, which is the maximum range is 5 micro meter.

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Parameters	Micro USM	Macro USM
Abrasive particle size, μm	Within microns (0.5 to5 μm)	Tens of microns (50 to 300 μm)
Static load	Gram force	Kilogram force
Tool feature size (mm)	Within 0.5	Usually >1

Then as far as abrasive particle size is concerned, so here also a significant difference is there. In case of micro USM the maximum particle size used is 5 micron, whereas in case of macro USM the particle starts from 50 micron and it can go up to 300 micron or so. In the recent trend in micro USM is where the less than 1 micron particles are being used and this is giving very good results as well. Then as far as the static load is concerned, the in case of micro USM it is in the gram force, whereas in the macro USM it is in the range of kilogram force.

As far as the tool features are concerned, tool features are nothing but that defines the size of the tool. Let us talk about diameter in terms of millimeter of the tool. So, it will be within 0.5 millimeter in case of micro USM and usually it is greater than 1 millimeter in case of macro USM. So, thereby we can see now the differences between the micro USM as well as macro USM, which is to a very generalized extent, it is the micro domain of the ultra basic ultrasonic machining is being performed.

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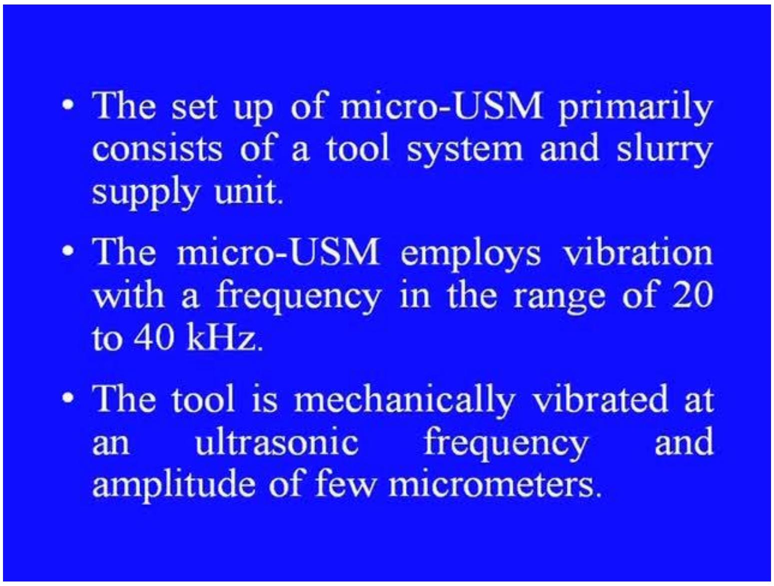

The setup of micro USM primarily consists of a tool system and a slurry supply unit. The micro USM employs vibration with a frequency in the range of 20 to 40 kilohertz again. The tool is mechanically vibrated as in the case of normal USM at an ultrasonic frequency and amplitude of only few micro meters. The abrasive slurry, which is a mixture of irregular shaped, fine abrasive particles usually in the range of 0.5 to 5 micro meter and a liquid medium is fed into the gap between the tool and the work-piece. This is similar to what we do in the normal USM process. As the vibrating tool head, hits the free abrasives in the slurry, they attain momentum and impact upon the target work-piece location.

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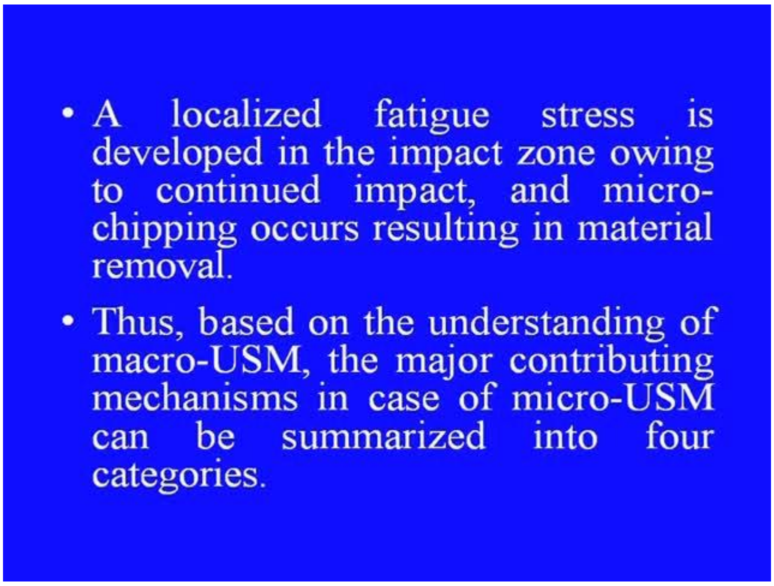

Then a localized fatigue stress is developed in the impact zone, owing to continued impact and micro chipping occurs resulting in material removal. Thus based on the understanding of macro USM, the major contributing mechanisms in case of micro USM can be summarized into four categories. As in the case of macro USM we have already discussed in details about these mechanisms of material removal. So, in case of micro USM as well these mechanisms are found to be no different so far, because we never know what other things will evolve in the days to come, and the researches in this area are still in progress.

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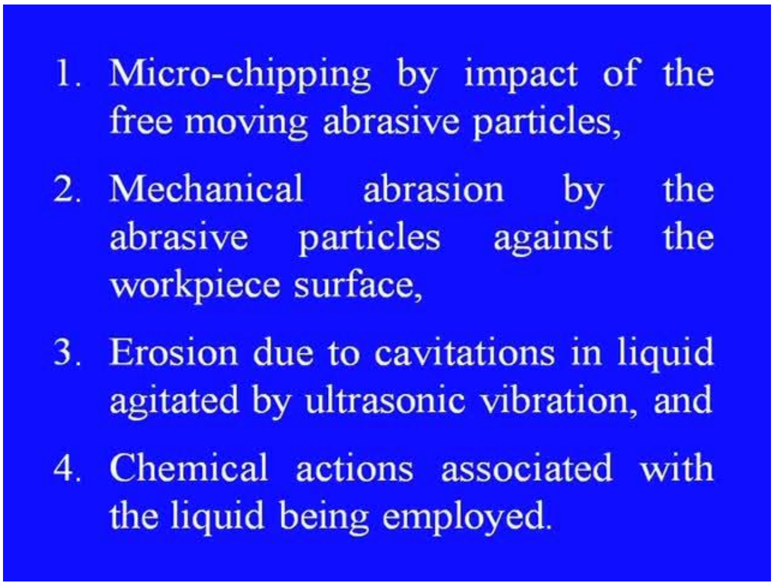

So, to say the intensive research are yet to take place and for the time being, let us summarize these mechanisms into these four categories like micro chipping by impact of the free moving abrasive particles. Number two, mechanical abrasion by the abrasive particles against the work-piece surface. Then number three, erosion due to cavitations in liquid agitated by the ultrasonic vibration. Then the chemical action associated with the liquid being employed. So, these are the main four mechanisms that involve micro ultrasonic machining. On the basis of tool head micro USM can be divided into two major types, mode one type and mode two type.

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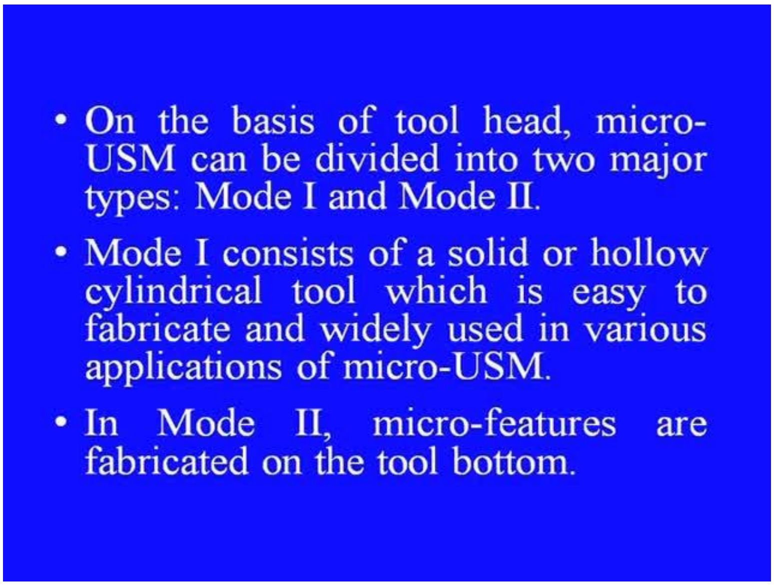

In mode one type, this consists of a solid or hollow cylindrical tool, which is easy to fabricate and widely used in various applications of micro USM. In mode two, micro features are fabricated on the tool bottom. The tool functions as a pattern and it travels vertically towards the work-piece. Therefore, micro features can be replicated on to the work-piece in one sinking operation. A unique benefit of this type of micro USM is to realize a parallel production of many identical simple features like gang drilling. We can have simultaneously number of holes drilled using number of tiny features, micro tools.

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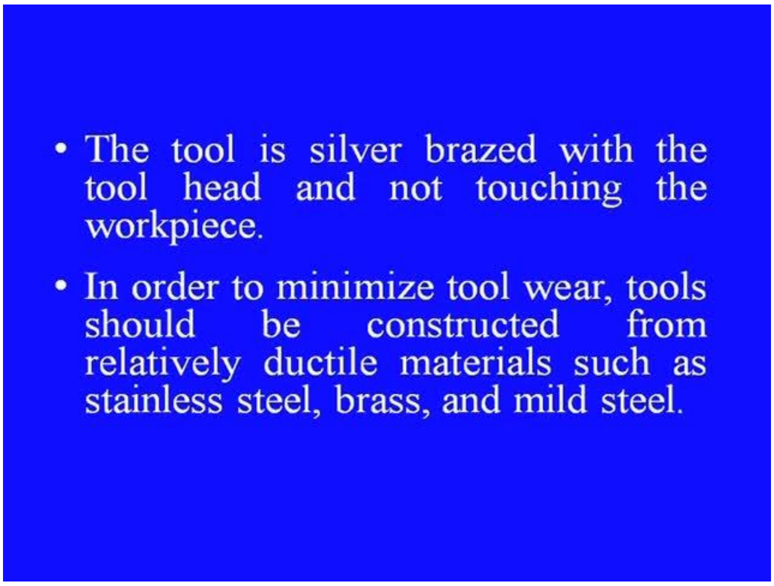

The tool is silver brazed with the tool head and not touching the work-piece. In order to minimize tool wear, tools should be constructed from relatively ductile materials, such as stainless steel, brass and mild steel. As in the case of macro USM, we have already discussed, low carbon steel, stainless steel, brass, these are some of the preferred tool materials, as far as their toughness is concerned and as far as their hardness is concerned.

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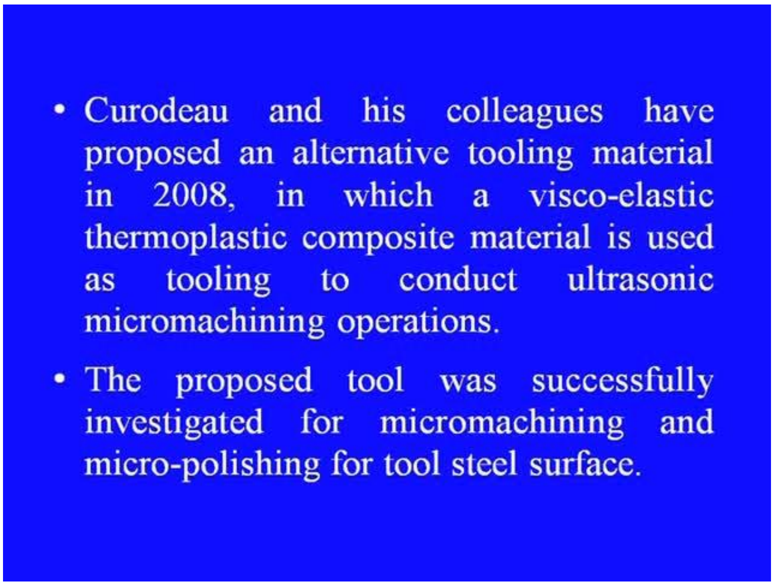

Curodeau and his colleagues have proposed an alternative tooling material in the year 2008, in which a visco elastic thermoplastic composite material was used as tooling to conduct ultrasonic micromachining operations. The proposed tool was successfully investigated for micromachining and micro polishing for tool steel surface. However, this material is yet to come in a big way, in the commercial market. The machine tools for USM range from small table top sized units to large capacity machine tools.

All USM machines share common sub systems, regardless of the physical size or power. That means in case of micro USM as well the same components that was necessary, as we have discussed in earlier sessions, for getting of workable ultrasonic machining system, the same subsystems will be required for realizing this micro ultrasonic machining as well.

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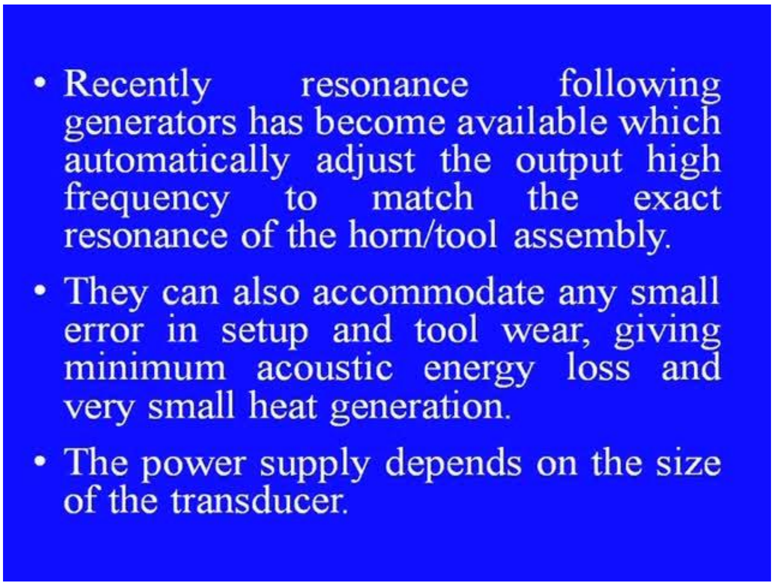

Recently resonance following generators has become available which automatically adjust the output high frequency to match the exact resonance of the horn or the tool assembly. This is an advancement as far as this tool is concerned, in which this matching of this frequency is very, very important and this is being automatically adjusted nowadays. They can also accommodate any small error in setup and tool wear, giving minimum acoustic energy loss and very small heat generation.

These two are major factors, the acoustic energy loss will reduce the process efficiency as well as the heat generation will also bring down the efficiency of the machine or the productivity of the process will come down. The power supply depends on the size of the transducer.

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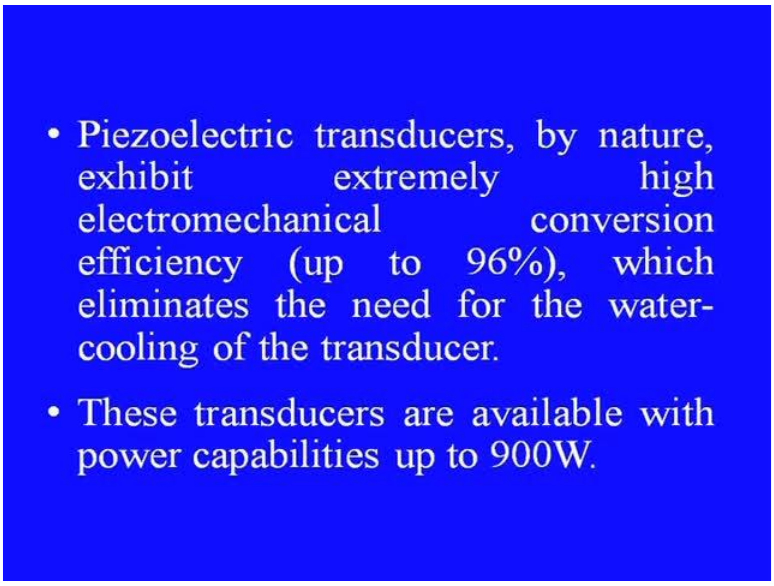

Piezoelectric transducers by nature exhibit extremely high electromechanical conversion efficiency up to 96 percent, which eliminates the need for water cooing of the transducer. Otherwise this heat generation in the transducer is also a major problem unless we take away or remove the heat, in through some mechanism the transducer may get malfunctioned, because of the overheating condition. Therefore, in many cases this separate cooling or additional cooling is is suggested or interrupting operation of the transducer is suggested. These transducers are available with power capabilities up to 900 watt.

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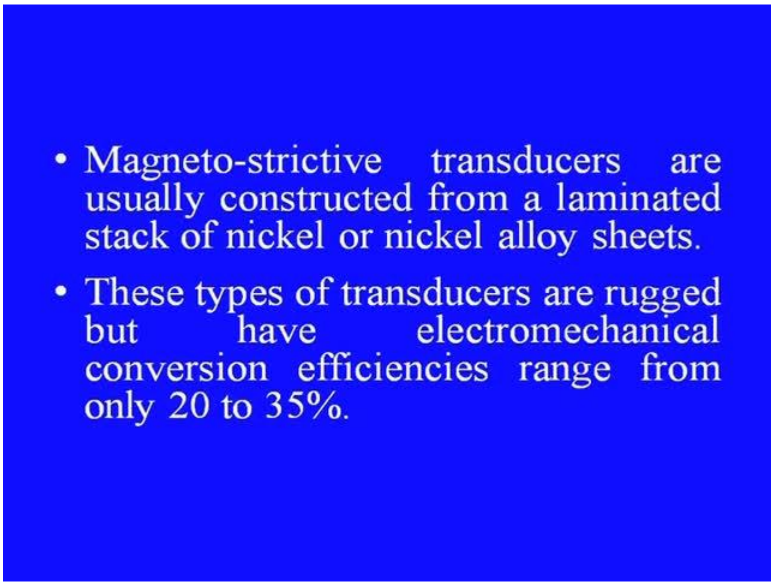

Magneto strictive transducers are usually constructed from a laminated stack of nickel or nickel alloy sheets. These types of transducers are rugged, but have electromechanical conversion efficiencies ranging from 20 to 35 percent. Thus we have seen, this is much less than that of piezoelectric transducers.

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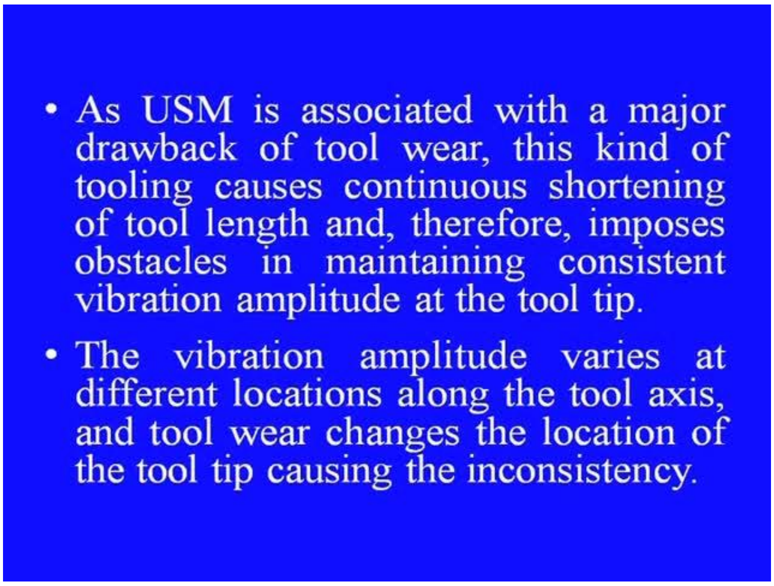

As ultrasonic machining is associated with a major drawback of tool wear, this kind of tooling causes continuous shortening of tool length. Therefore, imposes obstacles in maintaining consistent vibration amplitude at the tool tip. So, this is a major problem, as far as the maintaining of the vibration amplitude is concerned.

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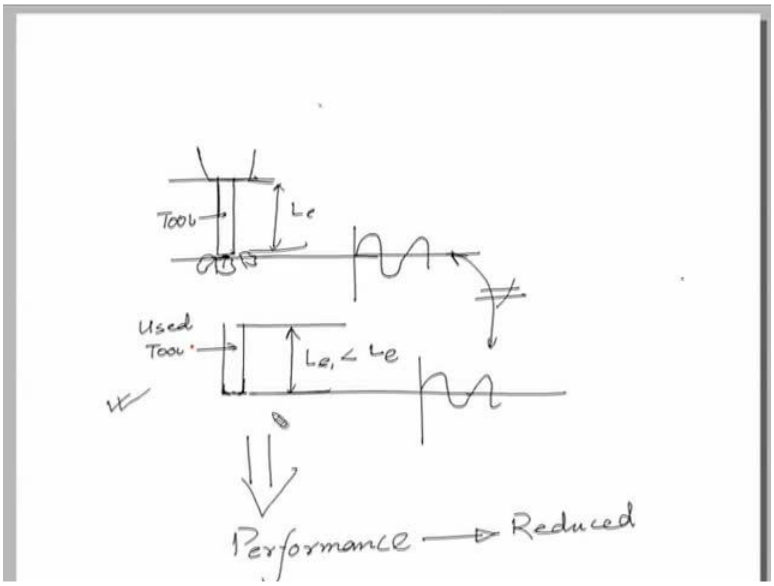

Say for example, the tool tip is having this much of length, say this is this is the length of the tool. So, this is effective length of the tool, now for this tool length, so the parameters at this tool tip, that means whatever the amplitude of vibration that we will be getting in turn the energy and the frequency of this vibration, so that will be fixed. Now, if we start machining with this length, say this effective length length of this tool, then the machining characteristic will be at particular level.

Now, in due course of time if because of the striking abrasive particles, it strikes the tool tip and the tool tip gets shortened like this. In fact it will be rounded as well like this because of the continuous striking of the abrasives and the tool length becomes say L e 1, where L e 1 is less than L e. So, this is tool, you can say used tool used tool. Then the characteristic whatever we are getting, the vibration characteristics and the energy available here will be different.

So, this and this will not be same, will never be same and therefore, this will ultimately affect the performance of the process, process performance. This will in in fact, this will be reduced. Thus this is very important that the tool length or the tool dimension remains same while working with USM. The vibration amplitude varies at different location along the tool axis, that is what just now we have discussed. If the length reduces then the vibration amplitude will will no longer be similar.

Therefore, consequently we will not get the similar kind of performance from this same tool, although same material same tool, but because of the change in the length, effective length the characteristics will be different. Tool wear changes the location of this tool tip causing inconsistency in machining.

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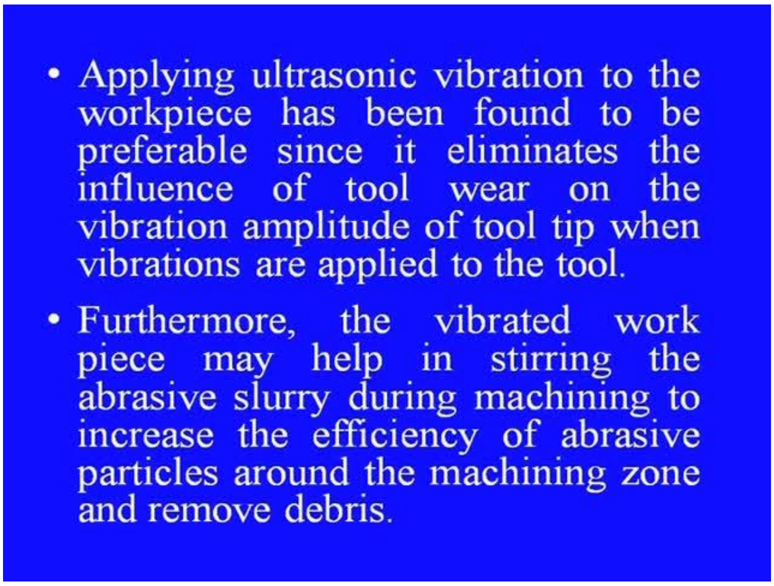

Applying ultrasonic vibration to the work-piece has been found to be preferable, since it eliminates the influence of tool wear on the vibration amplitude of tool tip, when vibrations are applied to the tool. This was basically the motivation while developing the version, where the ultrasonic frequency will be given to the work-piece itself instead of the tool. Here the dimensional change due to the wear of the wear of the tool will not affect the working parameters.

That is the change in the amplitude of this process and therefore, the process is advantageous. Furthermore the vibrated work-piece may help in stirring the abrasive slurry during machining, to increase the efficiency of the abrasive particles around machining zone and remove debris. This is another advantage, as far as this vibration applying to the work-piece is concerned.

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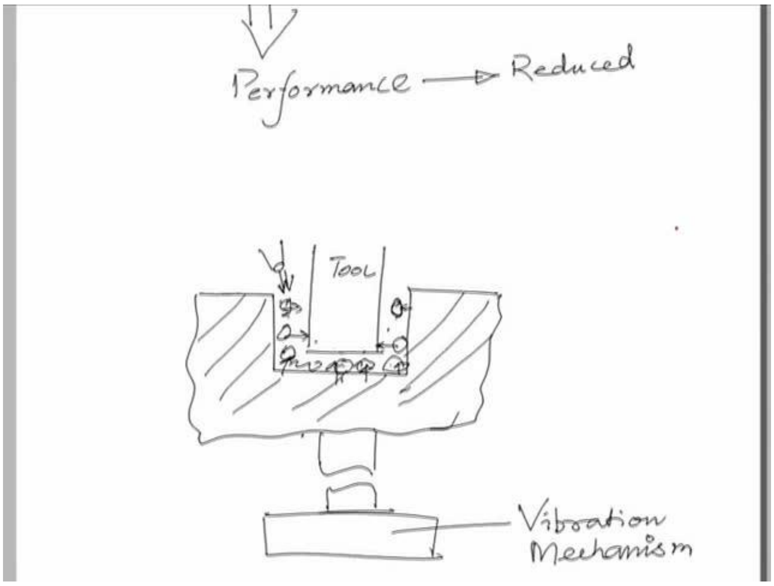

So, this can be thought of like this, say this is work-piece and if we have some mechanism to vibrate this work-piece somehow, say with the help of some mechanisms here. We are vibrating this work-piece, this is some vibration mechanism mechanism and this is giving to this, then while vibrating, so the the abrasive particles or the slurry that is coming in contact with this. So, this will also be, if this is vibrating then this will also be kept on vibrating because of the work-piece.

So, this will hit the work-piece, this will hit the abrasive particles and keep them vibrating in the machining zone, instead of getting clogged here inside this. The effectiveness of these abrasive particles will increase, in this way. Since, this will be kept on moving, therefore there will be possibility for the new abrasives to enter into this zone and the continuation of this machining process.

Now, let us see further advancements in the micro USM technology. There are evidences of drilling, an array of micro holes by micro USM using cemented carbide, multi tool assembly having a diameter of even 18 micro meter. So, this tool holder can be something like this, which we can use for gang drilling sort of applications.

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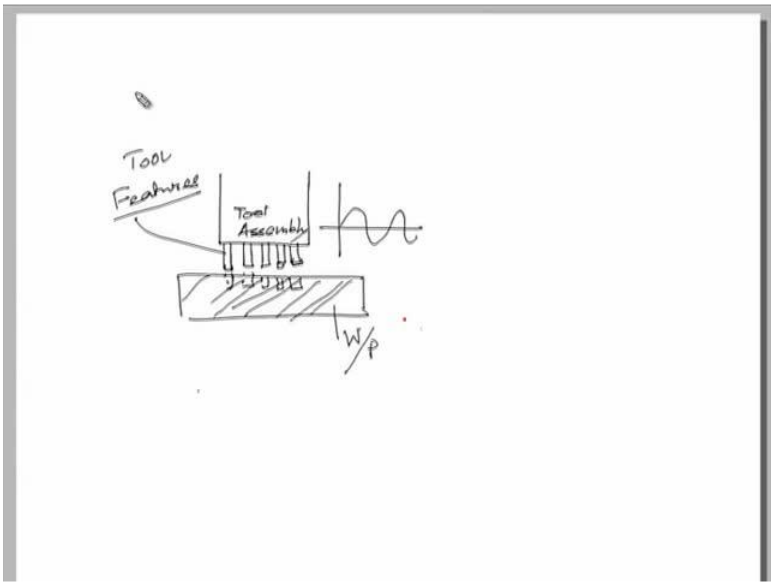

So, here if a tool holder instead of having single tool, if we can have a number of tool, array of tools something like this, something like this then on a single work-piece, single work-piece at the same time same time this is tool. We can say tool assembly instead of single tool. We can say this is a tool assembly and this is again this is vibrating at the same frequency and then this can cause simultaneously the holes, as the number of features present here.

Therefore, the holes produced in a single go can be up to the number of features that we are using. Features, these are tool features we can say, tool features, this is the work-piece. Drilling was performed four times and a total of 64 holes could be fabricated with an oscillation amplitude of 0.8 micrometer with only 0.8 micrometer. One can even drill 64 holes, that means this indicates that the process performance have been enhanced.

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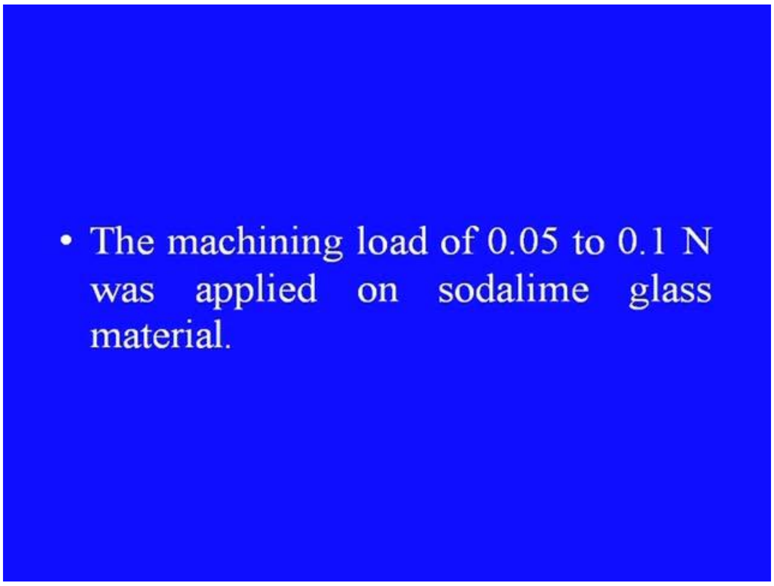

Machining of, machining load of 0.05 to 0.1 Newton was applied. In order to machine, the soda lime glass material, so this load is also considerably very, very less 0.1 Newton is quite small load. In an extreme attempt, micro USM was used to drill micro holes of diameter only 5 micron on silicon and soda lime glass. The measure of force to improve the micro USM process performance are to increase its throughput by using novel micro tooling technology. Especially for mode two micro USM, which is also called width pattern tool, micromachining width pattern tool.

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Micro USM with a single tool had so far been carried out on hard and brittle materials. This we have been already discussing for several times, however it is time consuming for drilling multiple holes, which is often a requirement for application of micro holes. Thus a micro EDM has been used to drill parallel holes, which is later used to produce micro cemented carbide multi tool using reverse micro EDM. The multi tool was further used in mode two micro USM.

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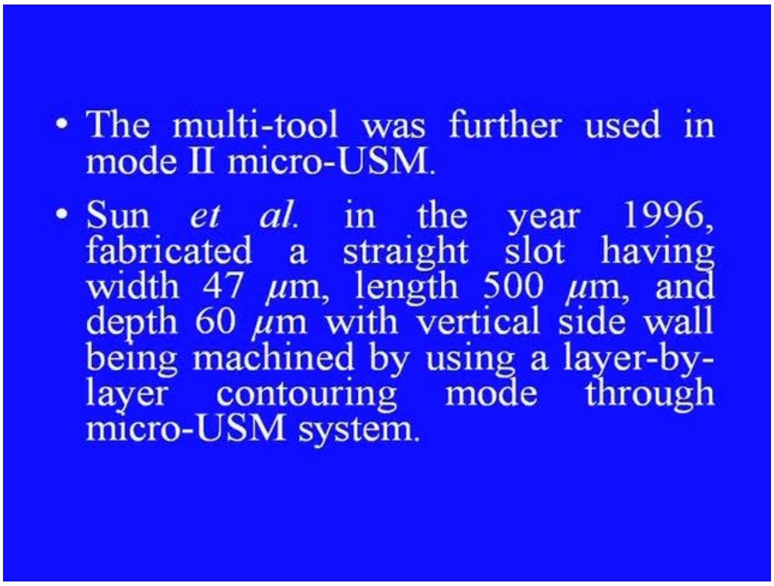

Sun et al in the year 1996 fabricated a straight slot, having width of only 47 micro meter, and length of 500 micro meter with a depth of 60 micro meter with vertical side wall being machined by using a layer by layer contouring mode through micro USM system. This is considered to be one of the first attempts of using this micro ultrasonic machining.

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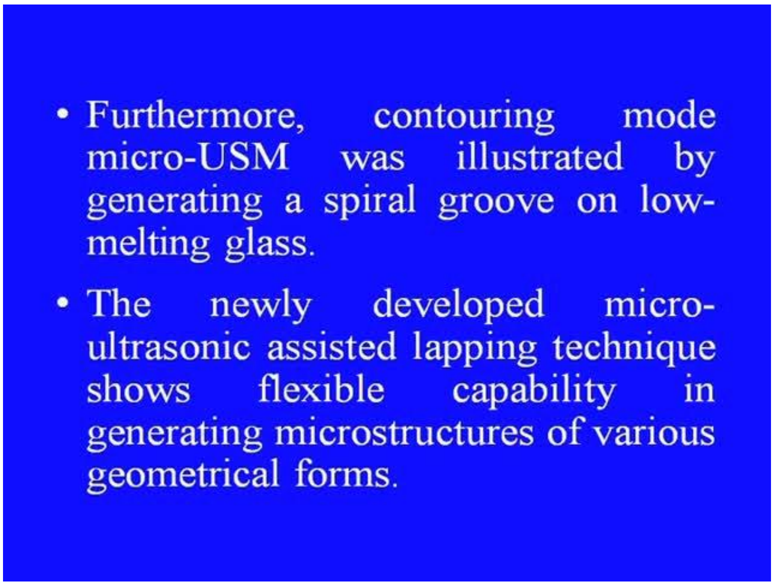

Furthermore contouring mode micro USM was illustrated by generating a spiral groove on low melting glass. These are some of the advancements in these technologies. The newly developed micro ultrasonic assisted lapping technique, shows flexible capability in generating micro structures of various geometrical forms.

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Major micro USM process capabilities can be summarized in the following table. However, there are many technical constraints to be overcome like the achievable concave feature size, aspect ratio and surface roughness limits as well as an operational issue incurred by tool wear. So, these are the main issues as we have seen in micro features the tools, which are micro we call as micro features, if the tool is like this, in which the length is much more the slenderness ratio is much high.

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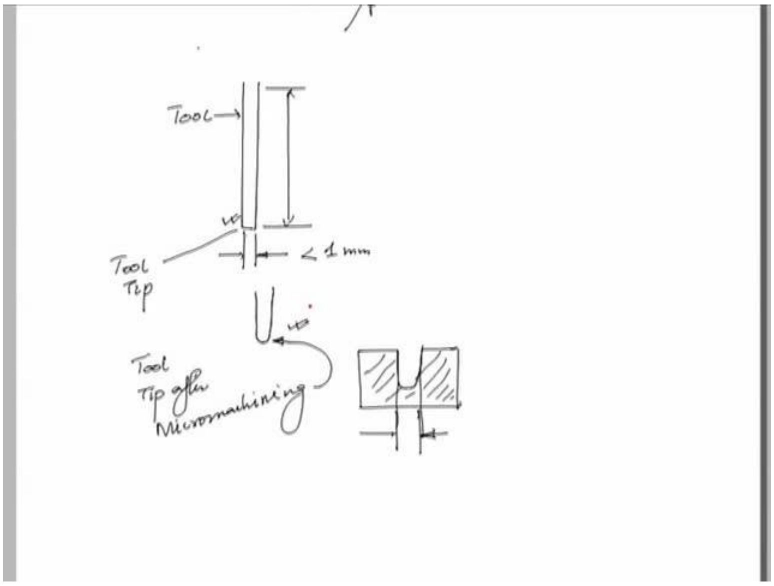

So, here the strength of the tool is to be considered it can buckle under the load and the wearing of this tool, if this is the tool wearing of this tool will be much faster than in case of a bulk tool. Since, this itself will be in terms of some less than less than 1 millimeter. Therefore, the tool itself will get rounded something like this. This is the tool tip, tool tip and this is the tool tip after micro machining like this. Now, if the tool tip becomes like this, then the feature produced in the corresponding work-piece will also be something like this instead of instead of a straight cylindrical hole, which should have been otherwise like this. Therefore, in micro USM basically the getting the tool feature, the geometric feature correct is a challenge and maintaining this tool feature throughout after machining is another big challenge. This particular table as displayed in the screen, shows the capabilities of micro USM.

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Table-2 Micro USM capabilities

Features	Capability	Reported by
Minimum diameter, μm	5 μm	Egashira et al., 1997 [15]
Depth *per* Length, μm	60 μm x 500 μm	Sun et al., 1996 [14]
Max. no. of features on single tool	16 micro-tools of 18 μm diameter	Egashira et al., 2004 [13]
Others	Array of pillars (Ø 280 x 6000 μm depth)	Boy et al. (2010), [18]

Here few characteristics or features are picked for comparison and who have first reported these features; that is also being shown. The minimum diameter that could be achieved as far as the micro machining is concerned using ultrasonic machining is 5 micron, that was reported by Egashira and his co researchers. This was of course, as early as in the year 1997. Then depth per length that was 60 micro meter into 500 micro meter, this was reported by Sun et al in 1996.

Then Egashira again in 2004, in the year 2004 reported the maximum number of features on a single tool. He used 16 micro tools of 18 micrometer diameter on a single go and then Boy et al has reported array of pillars with diameter 280 micrometer into 6000 micrometer depth. That is 6 millimeter up to 6 millimeter depth he could achieve. Now, let us see few developments in ultrasonic assisted systems. Rotary ultrasonic machining this was already indicated, is one of the cost effective and hybrid machining processes available for drilling holes. It merges the material removal mechanisms of diamond grinding and ultrasonic machining, resulting in higher material removal rate, than that of obtained by diamond grinding of ultrasonic machining.

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Two major requirements for micro rotational ultra, ultrasonic machining are the micro sized abrasive, bonded tool and machining system capable of applying very small load on the micro tool with necessary feedback and control mechanisms. Some of the disadvantages of the EDM ECM and other non conventional machining processes could be overcome by ultrasonic assistance, in the form of hybridization. Nowadays, ultrasonic vibrations are being used successfully to enhance the machining capability of even micro EDM to handle, otherwise difficult to machine material like titanium alloy.

As we know, all know titanium is becoming more and more important popular in the industries because of its excellent properties light weight, but at the same time, they are very difficult to be machined here. This USM is one of the process, which is useful in machining even the titanium alloys also.

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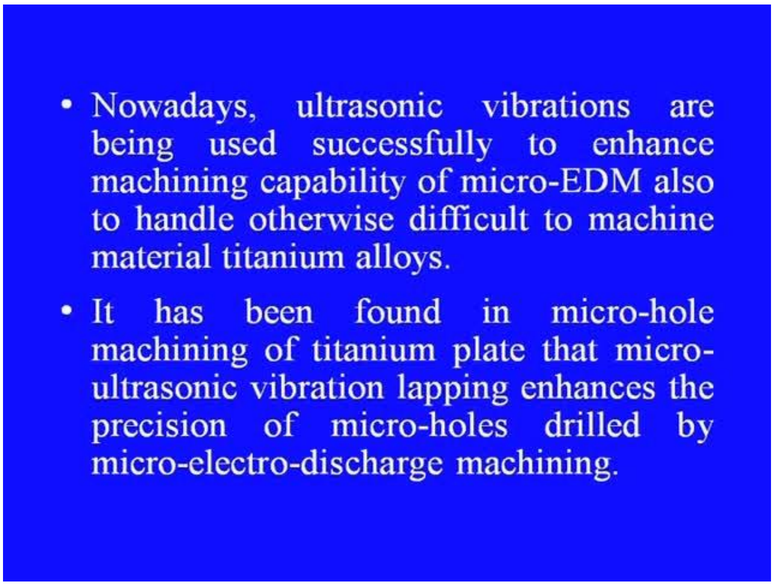

It has been found in micro hole machining of titanium plate that micro ultrasonic vibration lapping enhances the precision of micro holes drilled by micro electro discharge machining. Further USM assisted turning is also claimed to reduce machining time work-piece residual stresses and strain hardening and improve work-piece surface quality and too life compared to conventional turning.

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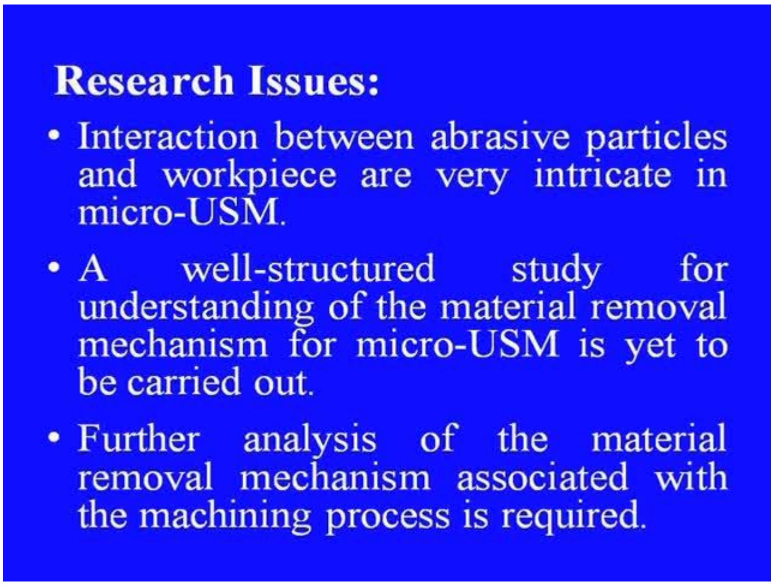

Now, let us have a look at the research issues. We have discussed many things regarding ultrasonic machining, its variants and types and as well the new developments in ultrasonic machining, in the form of in particular micro ultrasonic machining. Now, let us see some of the issues those needs to be addressed further. One such is interaction between abrasive particles and work-piece.

This is very intricate issue and as far as the micro USM is concerned, it needs to be further addressed. A well structured study for understanding of the material removal mechanisms, for micro USM is yet to be carried out. So, far we are going by the guidelines for macro USM. Another point could be further analysis of the material removal mechanisms associated with the machining process that needs to be addressed.

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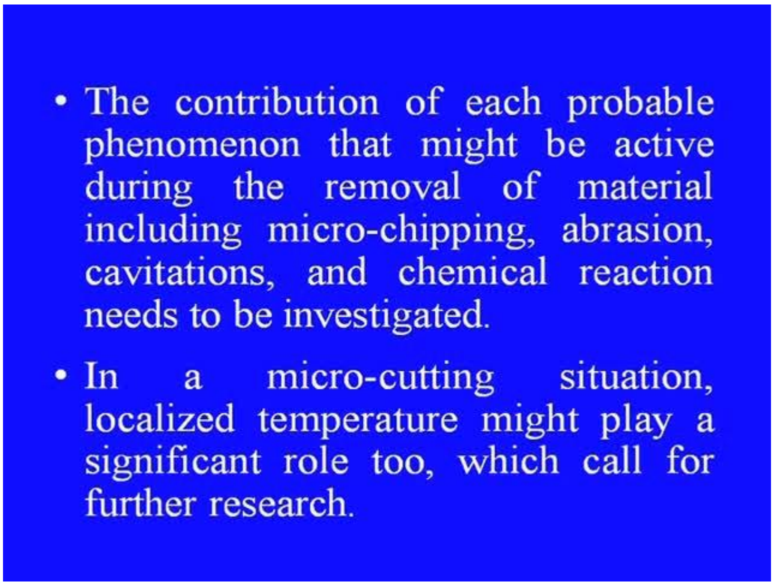

The contribution of each probable phenomenon; that might be active during the removal of material including micro chipping, abrasion, cavitation and chemical reaction needs to be investigated. In a micro cutting situation localized temperature might play a significant role too, therefore these needs to be evaluated. The process output parameters such as material removal rate and surface roughness, depend mainly on the physical or mechanical phenomenon at the machining gap. So, that also need to be evaluated. In such processes many research issues can be originated from the practical requirements, such as surface finish and existing limitations such as serious tool wear, particle size and surface finish of the process.

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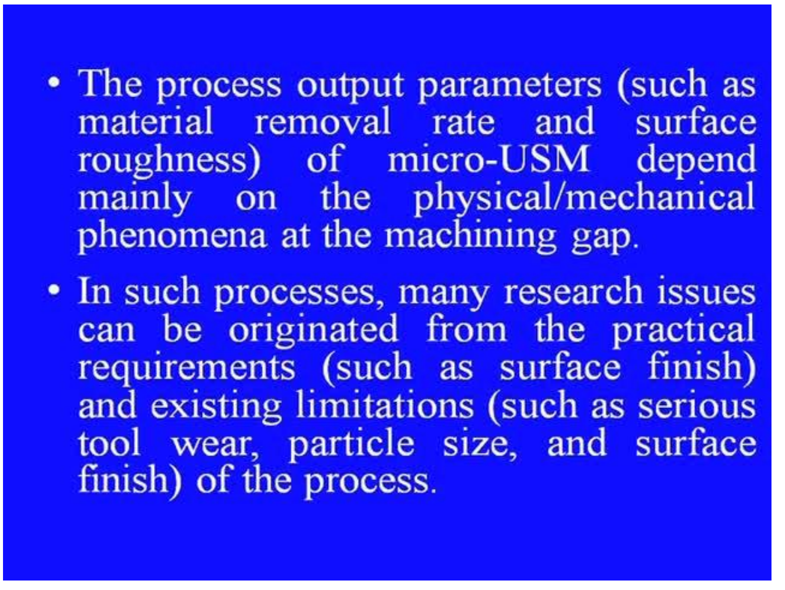

So, this needs to be sorted out from case to case basis. Studies on process capabilities and process modeling are few aspects that can contribute immensely towards the making the process cost effective. Micro tooling is another aspect, which could contribute significantly towards the process capability and such issues need to be addressed as early as possible.

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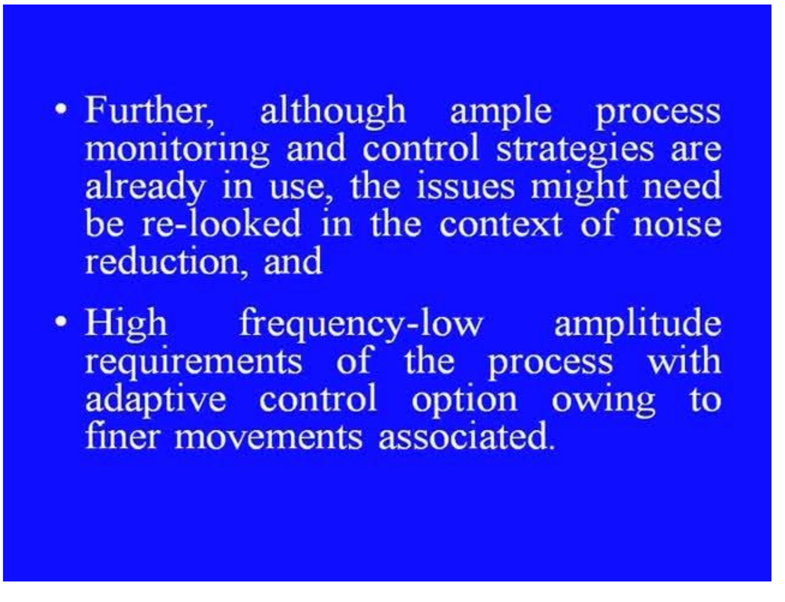

Although ample process monitoring and control strategies are already in use. The issues might need be re-looked in the context of noise reduction. Noise is as we know is associated with ultrasonic machining process. However, this is not friendly as far as the operator is concerned or the environment is concerned. Therefore, this issue needs to be sorted out or addressed. High frequency, low amplitude requirements of the process with adaptive control option owing to finer movements associated can be investigated.

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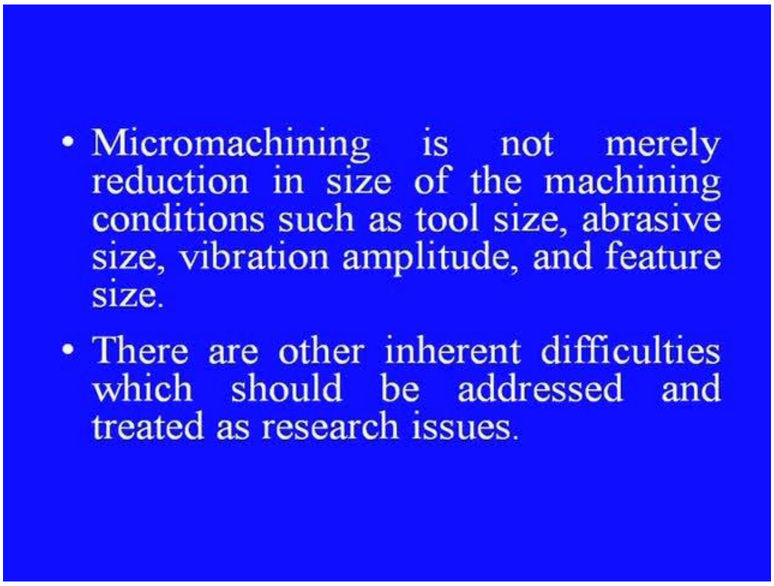

Micro machining is not merely reduction in size of the machining conditions such as tool size abrasive size vibration amplitude, and feature size. There may be other issues which needs to be sorted out, as far as I I was discussing just few minutes back. The problems associated with the small size tools could be much different from that of a bulk tool. The wearing phenomena, the temperature phenomena and the load phenomena, can cause a big difference between the bulk material removal process and the micro machining process. There are other inherent difficulties, which should be addressed and treated as research issues.

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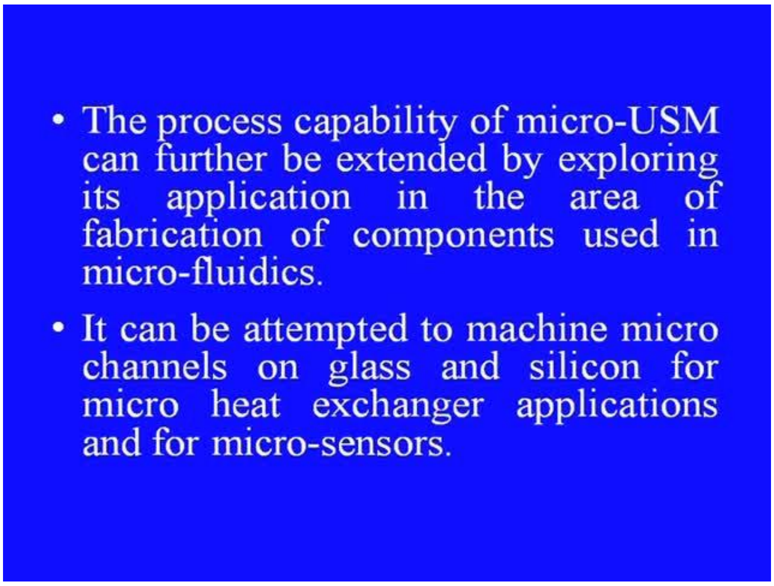

The process capability of micro u s m can further be extended by exploring its application in the area of fabrication of components used in micro fluidics. It can be attempted to machine micro channels on glass and silicon for micro heat exchanger applications and for micro sensors, which are very potent areas as far as the micro channels are concerned. Micro channels can be manufactured or fabricated using micro machining techniques, such as micro USM. we have already seen other techniques, which are already in process, most of them are like good for 2 D micro machining. But this is one of the process, micro ultrasonic machining is one of the potential processes, which is capable of machining 3 D channels or 3 D features as well.

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Potential applications of micro USM with rotated tool include the production of high aspect ratio micro holes, which has got less than 100 micro meter in diameter, in silicon and glass wafers, which are in great demand for pressure and low flow sensors. Then various specific applications that include drilling of small holes in helicopter power transmission shafts and gears. These are some of the potential applications, where micro USM can be very, very useful.

Machining of watts bearings and jewels slicing semiconductor components; for example, cutting circular wafers and drilling small holes in borosilicate glass. These are some of the other applications, potential applications of this process, which needs very finer control of the machining process and very finer cuts on the work-piece. Ultrasonic machining can also be efficiently used to micro machine as well as micro polish, a tooled steel surface with a thermo plastic tool.

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The micro USM process can be extremely useful for the semiconductor industry, as we have already discussed about this, as this industry needs processing of characteristically brittle materials. The applications of the process can also be explored for processing metal based materials relatively ductile with suitable adaptations, which can be of high demand in micro fluidics and heat transfer applications. As already we have discussed about titanium based alloys, which are typically or relatively you can say ductile than that of ceramics or glasses or most of this semiconductor materials.

However as far as the increasing popularity of titanium and alloys are concerned, this can be one of the materials in future and that needs to be processed very efficiently by some means, where micro USM can be very useful. Now, let us summarize what we have discussed in this session. We have seen the details of micro USM and advancements in its technology, we have seen the new trends and the research issues in micro USM and the potential applications where it can be applied. I hope this session was informative and of course, knowledgeable as well.

Thank you.