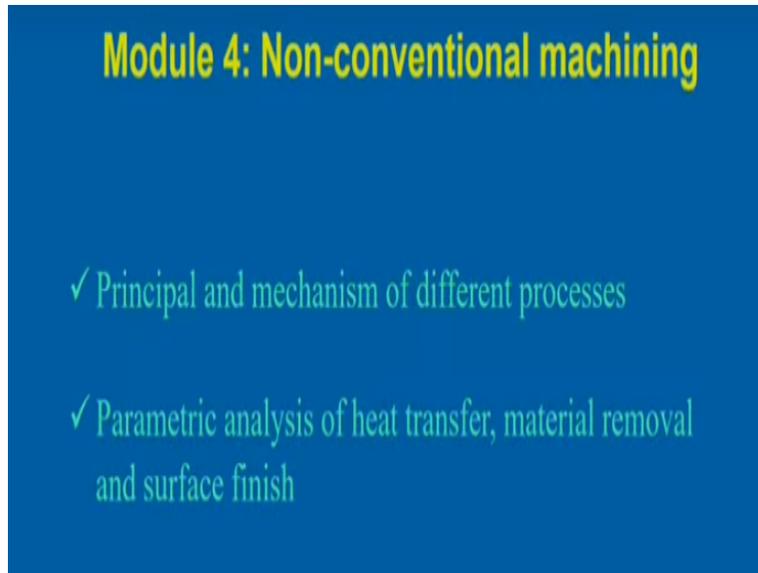**Mathematical Modelling of Manufacturing Processes**
Swarup Bag
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Lecture – 12
Principal and mechanism at different processes-1

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Hello everybody, so far we have discussed the conventional machining processes. There are lot of advantages as well as disadvantages in the conventional machining process. But conventional machining processes is having some difficulties. Specifically if we want to do some kind of non-regular geometric shape.

If we want to create if we want to do machine, we create that kind of different complex geometrical shape or maybe not very straight channel, maybe if we need to there is of course a channel requirement. So in that case non-conventional machining processes is the most suitable one.

So now we will discuss different non-conventional machining processes and of course modelling approach in the sense that our in this case we will try to limit our discussion only to estimate what is the material removal rate and maybe based on that parametric analysis. So most of the

cases, the non-conventional machining process, the modelling approaches becomes complex and of course it needs various specific treatment.

If we want to do modelling of particular non-conventional machining process whether in general we can say that there is a limitation of application of the maybe heat transfer equation straight forward we have done in case of fusion welding processes. So we will try to discuss only on the what are the maybe the order of magnitude in the order of what parameter dependency of material removal rate.

Surface finish that kind of relative comparison with respect to the different set of parameters and that we will try to discuss only that point of view. But in general in non-conventional machining process, first we look into that principle and mechanism of the different modelling processes. Then parametric analysis of heat transfer, material removal surface finish of course the heat transfer mechanism is very limited in these cases.

But other some kind of mechanical analysis is more relevant in case of non-conventional machining process. So first look into that so overall what are the different types of the non-conventional machining process and what we can do the modelling things.

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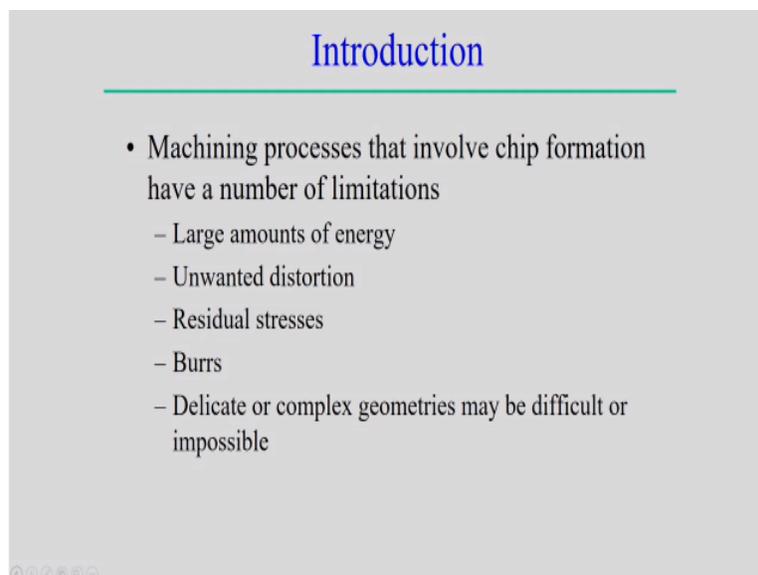
So definitely the non-conventional machining process developed because there are certain difficulties, certain problems in case of conventional machining processes. So we know that conventional machining process there is a generation of the chip formation. And of course it is a in terms of limitation we can say that large amounts of energy requirement in case of non-conventional machining processes.

We can expect some kind of unwanted distress and because large amount of the heat generation and that heat generation may not be suppressed. Sometimes suppressed up to certain extent by using kind of cutting field but not that much extent. So it unwanted distortion may comes from the high strain rate and maybe at temperature. Some crystallization also happening on the surface.

Maybe this generation of the residual stress, formation of the burrs okay. And of course the mainly limited to create delicate complex geometrics and very fragile and brittle material, machining of conventional machining processes really very difficult. So in that sense, non-conventional machining processes advantages.

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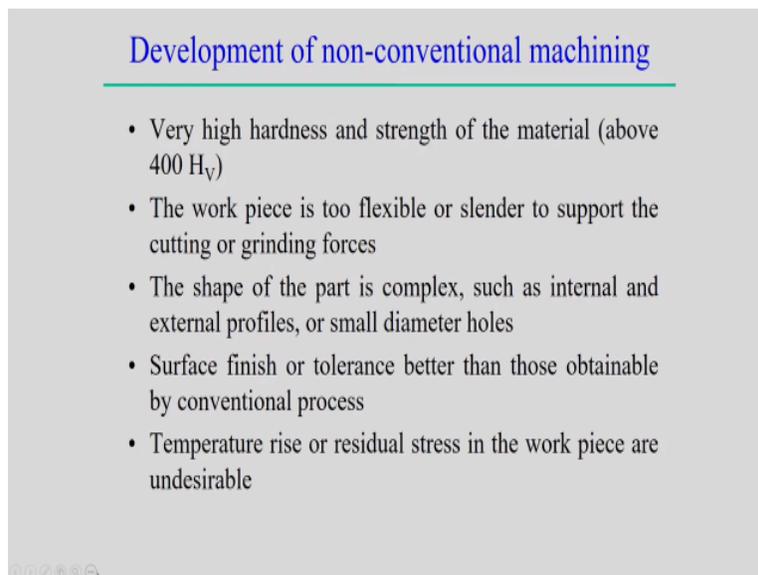
Development of non-conventional machining

- Very high hardness and strength of the material (above 400 H_V)
- The work piece is too flexible or slender to support the cutting or grinding forces
- The shape of the part is complex, such as internal and external profiles, or small diameter holes
- Surface finish or tolerance better than those obtainable by conventional process
- Temperature rise or residual stress in the work piece are undesirable

But in what prospective different non-conventional machining process has been developed. First we look into this work piece hardness is very high strength very high having material having

very high hardness above 400 Hv. In that cases there is a difficult of application of the conventional machining process.

So in that sense the nonconventional is most suitable and of course if work piece is too soft or too flexible that may not sustain with the application of the cutting forces or grinding forces. So in that case this type of difficulties may be possible to overcome in case of nonconventional. Of course we already mentioned that very complex steps such as internal and external profile or maybe a very small diameter holes if we want to create, so then non-conventional machining processes is the most suitable one.

Surface finish, tolerance and of course if we want to do kind of different finishing operation if we want to **so** non-conventional process is more suitable. Then temperature rise and residual stress definitely in this cases that temperature rise is very limited in case of non-conventional machining process and that is the main difference. And of course there is a temperature rise and micro structural changes is really in that cases.

So residual stress generation in the machining component using non-conventional machining process is very limited. So in that sense it is very much advantageous as compared to the conventional machining process.

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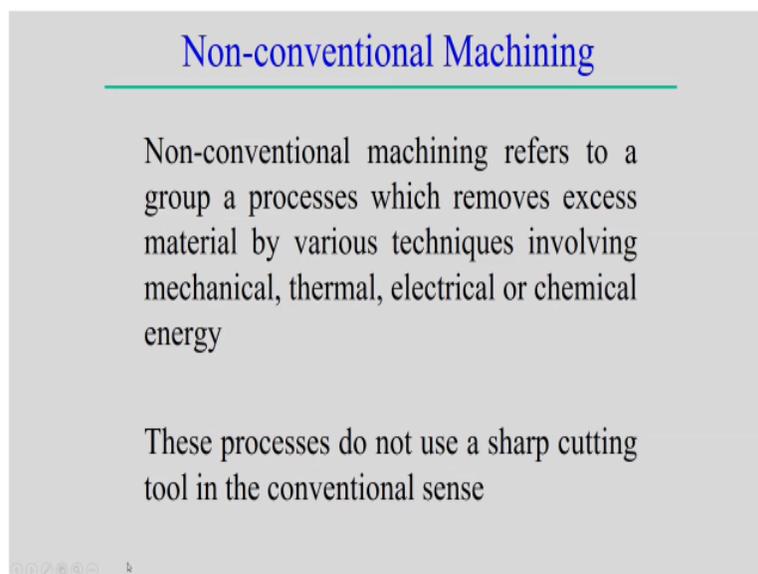
Non-conventional Machining

Non-conventional machining refers to a group a processes which removes excess material by various techniques involving mechanical, thermal, electrical or chemical energy

These processes do not use a sharp cutting tool in the conventional sense

Non-conventional machining refers to a group of processes that removes that excess material by using if we look in different techniques involving some mechanical energy, application of the thermal energy application, application of the chemical energy or application of the electrical or electrochemical energy. But the main difference is from conventional machining process, it is not requirement of any kind of very sharp cutting tool what we use in case of conventional machining process.

And of course in general, the rate of the material removal is very less in case of non-conventional machining process as compared to the conventional processes. Because the non-conventional machining process the main focused it to achieve the to deserve difficult different types of the material may be very difficult to machine materials. For example, very brittle material, glass that kind of material.

Or if we want to get one to achieve very good surface profile, very good finish. So in that sense the material removal rate is impractical whether the other aspect is more practical in that cases. So that is why we focus only on the non-conventional machining process where there is a requirement of the very fine hole. For example, very good surface finish and very complicated shape, which is not possible using the conventional machining process.

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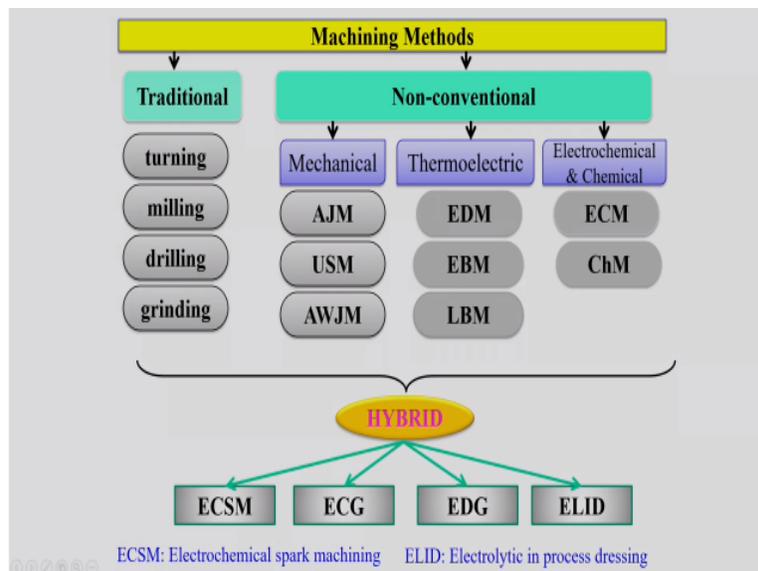
Now we will look into that what are the different machining methods. Traditional machining methods, so as we know there are several types for example, turning, shaping, planning, milling, drilling, grinding. These are the traditional machining processes that we have already discussed. But if we look into that non-conventional processes where which is different from the conventional processes.

where we can use the simply mechanical energy to develop the process. For example, abrasive-jet machining, ultrasonic machining, abrasive water jet machining and these are the apart from that even there are other types of the non-conventional machining process has been developed by using some kind of mechanical energy or if we look into the thermoelectric energy.

So there is non-conventional process, the electro-discharge machining EDM, then electron beam machining, then laser beam machining. These are the typical thermoelectric energy is converted to used basically utilized for the machining purpose. And then electrochemical or chemical energy source can be used for machining purposes. For example, electrochemical machining and only chemical machining.

So all principles we will try to discuss one by one. But apart from that, if of course the main difference traditional non-conventional machining processes is that we can achieve very good surface finish and desirable characteristics, it is possible to achieve which may not possible to assume the traditional.

But if we combined these two probably we can achieve increasing the material removal rate as well as the what are the difficulties in conventional process that can also be achieved by using the hybrid processes. For example, electrochemical sparks machining and this hybrid presses electrochemical grinding, so it is a grinding process and maybe merge with the electrochemical machining principle.

And then we can achieve advantages of both from traditional welding process, traditional machining process as well as from non-conventional machining process. Similarly electrochemical, electro-discharge grinding also possible and electrolytic in process dressing

ELID that kind of different type of the hybrid process and many more hybrid processes has been developed by using merging the concept of the conventional machining process as well as the non-conventional machining process.

So we will try to look into what are the principles, type of energy sources and what are the different medium are used for different process.

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Classification

Type of energy	Main process	Energy source	Tool	Transfer media	Mechanism of material removal
Mechanical	USM	Ultrasonic vibration	Sonotrode	Abrasive slurry	Erosion or Abrasion
	AJM	Pneumatic pressure	Abrasive jet	Air	
	WJM	Hydraulic pressure	Water jet	Air	
	AWJM	Hydraulic pressure	Abrasive-water jet	Air	
Chemical	CHM	Corrosive agent	Mask	Etchant or reactive environment	Chemical dissolution or ablative relation
Electrochemical	ECM	High current	Electrode	Electrolyte	Anode dissolution through ion displacement

We can get the idea that things that type of energy. what are the main processes? Energy sources, tools you have transfer media and mechanism of material removal over all we look into that. First. if we look into that mechanical energy if you assisted non-conventional processes. So these are the very common processes we use that ultrasonic machining USM, Abrasive jet machining ,water jet machining, Abrasive water jet machining defining ultrasonic machining energy sources are ultrasonic vibration**.**

So tool is the Sonotrode and then between the tool and the workpiece there is a passage of the Abrasive slurry. So that abrasive particles basically try to erode or clears the abrasion to the workpiece as well as the tool material. So here transfer media is the Abrasive slurry and because that is in contact with the work piece and the tool material and mechanism of material removal we can say the erosion or abrasion.

Similarly, Abrasive jet machining also is a recreation of the pneumatic pressure. So pneumatic pressure creates the jet of the Abrasive particles along with some kind of carrier gas and then abrasive jet impact on the workpiece and then, , that creates kind of erosion to the work piece surface. So transfer media in these cases is air. Similarly a water jet machining we just simply create a jet of water and that normally removes the material.

And of course the tool is the water jet directly used can as a tool to the workpiece for the cutting purpose or removing the material. and of course in this cases some sort of hydraulic pressure is required to create the jet. Similarly, combining principle of the abrasive jet machining and water jet machining it is abrasive water jet machining. So here taking the advantage of both water jet as well as the abrasive machining and then it creates the abrasive water jet and transfer media.

We can consider as a Air and of course then erosion or abrasion is the main mechanism to remove the material. So apart from mechanical energy. there may be the possibility of the chemical energy can be used, in non-compressible machining process. For example, CHM chemical machining here we can use the kind of energy source you can use the kind of Corrosive agent.

So transfer media, some kind of Etchant or reactive environment. So that would remove the material by the reaction and mechanism of the chemical dissolution or ablative relation is the main mechanism such that during the chemical reaction it removes the material. So definitely in this cases the thin layer of material removal is possible. We cannot compare the removal of the material as compared to just simply trending process in conventional machining process.

So here the rate of the material removal rate is very low in this cases and of course electro chemical machining process in this case high current it passes and then to the there is a tool is to tool metal we can use electrode and transfer media. The electrode is in contact with the work piece through the electrolyte, different types of the electrolyte we can use depending upon what type of material there is a need of the removal of the material.

So it says simply electro chemical machining is a kind of opposite action of the electroplating. Where we can just remove we can deposit a layer on the surface, but in this in machining process we just remove the layer by controlling the choosing of the electrolyte and the of course the choosing the different polarity of the electrode on the workpiece based on that and of course the mechanism is the anode dissolution rather than the deposition.

Here is the anode dissolution through iron displacement the missed anode that was the work piece reaction happened. Work piece is basically a dissolution of the work piece normally happens in this series and electrolyte with a high pressure this carry the dissolution part of the work piece.

This is the electro-chemical machining apart from that thermal energy can be directly used for the different machining, noncompliant machining process such as electro discharge machining.high voltage electron beam, Ion beam machining, Laser beam machining as well as the plasma Air machining.

So if you see electro discharge machining high voltage and they create a spark between electrodes. but in this case the spark. and that transfer media means that is marched the contact between the electrode or through some kind of a dilated fluid. So first melting and vaporisation is the main mechanism first melt or vaporize that part directly vaporize the part by the application of the thermal energy.

So that is the principle of the electrode discrimination then similarly ionized material in a energy source in case of a electrode removal machining here under the vacuum here the electron beam and that is simply melting and represent a particular that is localized zone. Similarly Ion beam machining laser beam machining the different thermal energy sources are used and tools all this cases for example electron beam directly use to remove the material.

In case of Ion beam machining Ion beam is responsible to remove the material. In case of laser, the laser energy or laser beam, that will be using in case a plasma machining basically plasma jet is used to remove the material. So, but all this mechanism are based on that melting and

vaporisation of the substrate material. so these are the basic classifications of the different types of noncorrosive machining.

Of course there are till there is a lot of machining a non-corrosive machining process has been developed but these are main non-corrosive machine that we are supposed to discuss here.

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> The tool need not be harder than the workpiece
>
> Small size non-circular holes cannot be produced by traditional methods but easily produced
>
> Machining of highly brittle material is not possible with traditional methods. e.g., Brass, Ceramics, carbides
>
> Machining of very soft material like rubber is difficult with conventional methods because producing the shear in the rubber is very difficult and the chips produced during machining of rubber will get adhered to the tool tip and blocking the tool tip.

What is the need requirement of the non-conventional machining processes? Definitely it is the one advantageous tool not necessarily be harder than that of the workpiece material that is the main advantage and that means sometimes the non-conventional machining process has been developed independent of the hardness of the tool and if pick up with respect to the conventional machining process is definitely the hardness of the tool must be greater than that of the workpiece material

But in case of non-conventional that limitation can be overcome. Small size non-circular holes can easily be produced by non-circular can be non-conventional machining process. So if there is a requirement of non-circular non-conventional machining processes is the best suitable in that case. Machining of the very brittle material very fragile material using traditional process is really very difficult.

For example mixing of brass, ceramics, carbides using conventional machining process is really very difficult. So in that case there is a need of kind of non-conventional machining process of course at the same time it is brittle it becomes very soft for example rubber it is a very difficult to during the machining operation and using conventional processes.

So in that case nonconventional is that one of the most suitable whether for the machining of the rubber and of course non-conventional machining process can produce much more complex concave kind of steps easily for producing non-conventional machining. So there is a need all these cases we point out that that we can find out the application of nonconventional processes when there is a having certain limitation of the conventional processes.

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First we start with the mechanical based processes ultrasonic machining, water jet machining, Abrasive jet machining and abrasive water jet machining and all this process we have tried to look into modelling approach in the sense that well try to do some kind of estimation of the metal removal rate and to some extent surface finish and all these cases the parametric approach is more suitable in case of non-conventional processes because the influence of the different parameters are really highly non-linear in that sense.

So most of the cases if we know the parametric approach means what is the role of individual role of the parameters to the process and we will try to correlate kind of statistical relation and

we assume by assuming certain relation in terms of geometric curve and then we find out what is the co-efficient of this lesson. For example if we do find out as fall in certain relation between the metal removal rate and different between the different parameters of the process.

So we find out we if we assume some kind of polynomial function then we need to try to find the what are the different coefficient of the polynomial by comparing the x by simply fitting this curve with this experimental data regression analysis can be followed in these cases so apart from doing the conventional way to find out how the modelling of the non-conventional machining process.

The other approach simply statistical modelling approach is more popular in case of a non-conventional machining process. But we will try to look into very basics things what we can model the model means here in the sense that we tried to estimate what are the mainly the metal removal rate for the different non-conventional machining processes.

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First start with the ultra-sonic machining process so definite ultra-sonic machining process can we can use the very hard and brittle material specifically for hard and brittle material. So easily chipping or rapture of the materials may happens and remove the material but how it happens simply oscillating tool and ultrasonic frequency maybe 80 to 20 kilohertz and with amplitude of the 10 to 40 micrometres.

So by application of the electrical energy we can utilize the vibrated energy here and then mechanical clear the mechanical vibration and then vibrated energy responsible for the removal of the material by creating that kind of in the range of the parameter range in that 10 to 40 micrometres is the amp here and 80 to 20 kilohertz is the frequency. So it is the simply the abrasive particles with this vibration.

The abrasive particles is a hammer basically impact on workpiece material as well as the tool material. So this where of the tool also happens in this process and but the vibration is actually transmitted to the abrasive slurry via tool. So tool actually transmitted the vibration energy to the abrasive slurry and then from the abrasive slurry then impact on the work piece. This way it transported the energy to remove the material.

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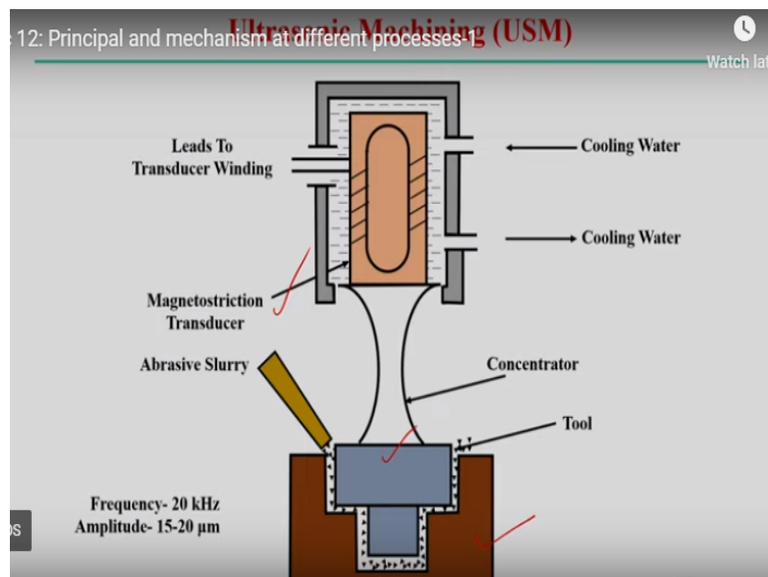
We can see the diagram a schematic diagram of this Ultrasonic machining process. So see there is a transducer also there here. So transducer is basically converting the electrical energy to the vibration and we can use this is the tool material and here you can see the tool material and this is the work piece material. So between the tool and the work piece there is an abrasive slurry feel with these things.

So tool is not in directly contact with the work piece rather tool is contact with the abrasive particles and then abrasive particles are in contact with the work piece. But in this case what it

transmits the vibrated energy to the tool that is a that is we use some kind of a concentrator can be used and of course in this case other systems it is part of the cooling water in and cooling water system we use.

Definitely the transducer is mainly the this part that creates the vibration from the electrical energy and frequency around 20 kilo hertz and amplitude 15 to 20 micrometre or it can be range up to 40 micrometre let us discuss this thing.

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Tool: To minimize the tool wear, it should be constructed of strong but ductile material

➤ Commonly used materials: brass, mild steel, stainless steel

➤ Harder the tool material faster the tool wear rate

Abrasives: (should be harder than the material being machined)

➤ To carry abrasive to the cutting zone and wash away the worn abrasives and swarf from the cutting zone

➤ Liquid help in material removal due to cavitation effect during return stroke of the tool

Now what are the typical characteristics of this ultrasonic tool? Tool material not necessary in this cases very hard but to minimize the tool where the constructed it is constructed of the relatively ductile material. So it helps although there must be some amount of the tool where during these things but if it very brittle material the metal removal may be very high rather if you use the ductile material so not exactly the metal removes by directly and the rupture of the material rather high plastic deformation may happen in case of ductal material.

So that is why it will reduce the amount of them where if we use the ductile material. So tool should be ductile material in ultrasonic machining process commonly used material brass can be used mild steel, stainless steel or normally used as a tool material but harder the tool material faster the tool wear rate. So that is the main thing in this process that we should not be very we should not use very hard tool in case of ultra-sonic machining process.

Then what is the role of the abrasives? Abrasives should be harder than the material because abrasive is actually in contact with the work piece. So abrasives should be harder than that of the work piece material. So then abrasives are cutting zone and then washed away the worn abrasives and swarf from the cutting zone. So worn abrasives the dual role first is the abrasive impact remove the brittles and at the same time once chipping the material and then work piece material along with the abrasive washed away from the work piece surface.

So of course in certain cases if there is a flow of the abrasive slurry the metal removal due to the cavitation effect sometimes is active and that normally happens during the heat transfer of the tool.

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MRR Modeling By M. C. Shaw [1956]:

Mechanical abrasion due to direct hammering of abrasive particles

Assumptions:

MRR ∝ volume of the work material per impact (v)

MRR ∝ number of abrasive particles impacting per cycle (N)

MRR ∝ frequency (number of cycles per unit time) (f)

All the impacts are identical

All the abrasive particles are identical and spherical in

If we look into the modelling part of abrasive machining process so we assume that mechanical abrasion occurs due to the direct hammering of the abrasive particles to the work piece what are the assumptions in this case? Definitely the metal removal rate is depends on the what way the particular impact on the workpiece and what is the amount of the volume from the work piece is removed per particle from single particle.

So that is why volume of the work material part impact is now material removal depends on this things then if we look into the metal removal in terms of the other parameters. So definitely it

say a number of abrasive particles per cycle so what are the now we count is what is the metal removal for one particular then we count what is the number of particles per unit cycle time then we count per unit time what is the number of cycles?.

So that is where all material removal depends on these three parameters. Now finally we can say that volumetric in terms of the volumetric metal is MRR is the metal removal rate volumetric metal removal rate is basically equal to the volume, impact then number of particles and finally what is the frequency sorry N is the number of abrasive particles per cycle and f is the frequency that is cycle per second that means finally it represent what is the amount of the volume removed per unit time.

So that represents the volumetric metal removal rate. If you multiply with density then it becomes mass metal removal rate but that units would be mass per unit time.

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What are we modulate? what are these things? first is that we assume that indentation caused by a impact of a rigid spherical particles of diameter d on the work surface. For example this is the work piece surface and some spherical particular impact on this thing diameter of the spherical particular d and of course diameter of the indentation is basically D and we assumed that it creates kind of depth =h.

So in terms of h,d, D and d/2 we can say this is basically d/2. Now from this triangle say O,A and B so triangle O,A and B we can find out that d/2 ,d/2 square=capital D/2 square+d/2 this O,A basically d/2-h square. So once you do this and we can find out that d by this expression D square=4dh-4 h square you can find out that things if is h <d then maybe we can neglect this part and then finally we can estimate D square=4dh and we can find out D=twice approximately twice root dh.

So then volumetric rate volumetric metal removal rate which is represented by v that means per impact of the worn particle what is the amount of the volume removed and then N is the number of particles impacting part cycle and then multiply by f what is the cycles per second. So I can say if L is the dimension the volume per time these represents the volumetric metal removal rate. What is the total volume per unit time removed?

Now once vNf so he can be represented like that v= small v the volume of the material that is removed per impact. So this creates this kind of profile so that we can consider this as a hemisphere 1/2 of the sphere having the diameter D. So then what is the volume? So 1/2 of the sphere volume/3 D/2 is the brittle this is the volume.

So this corresponds to the 1/2 of 4/3/8 so 1/6 pi D cube so this represents the per impact with one particle what is the amount of actually volume removed from the work piece surface. So put this is the v amount this is N this is f now we replace D in terms of h because h is the depth. So h if you put in terms of D capital D so D if we put this D here then it becomes twice//3rd pi dh is 3/2 Nf.

So this is the estimation of the volumetric metal removal rate and of course in this case the particle this if you see it is in terms of d ,h,n and f because d is the diameter of the particle which can be miserable quantity which can be measured, h is the measure up to the what is the depth it increases per impact, h can also be measured and then n is the number of particles per cycles can be measured the n and f is the frequency cycle per second.

So if all the parameters are known to us that we can easily estimate what is the approximate volume product. But of course in this cases we assumed that its creates exactly the is impacting all the under spherical particular but practically it may not be the very spiritual particular this can be kind of irregular shape and the second one is that when its impacted on the work piece surface it also creates a metal removal which is assumed that it clears the geometrics shape of a sphere having the diameter D.

Basically indentation diameter indentation that assumptions may not be correct in practical applications but applicant estimate if you know all these parameters with this assumptions assuming this spherical particles then we can estimate what is a metal removal rate in this case. Of course we can estimate other parameters also in ultrasonic machining process.

So mean speed of the tool actually the speed of the tool means speed of the tool is very low the mean static force can be estimated for example normally if we estimate the force F axis how it varies with respect to time t and of course this is the time axis but I say that is the one cycle time T and most of the it is normally found out that this variation of the force with the during this process normally you can find out such that this becomes corresponding.

So that Fi max maximum force this one and this is not normally happens over that small time I think we can say that is the delta t time there is a over a delta t time there is a rise of the force, force can create an goes to the maximum value of impact and of course therefore means static force applied on the tool must be equal to the mean force of the tool applied on the grains.

So a maximum impact force p assume this Fi max and that of course the maximum force raised over a small period of time delta t and then we can find out maybe average value which is in between is it a average value but over a cycle time t. So I think it is say average value is the F or you can say that sorry suppose this is F average time is F what is the amount of the this thing Fs impact during the impact delta t maximum below back impact force is given here.

So Fs can be integrated what is the force? it can be integrated the over the cycle time that this thing which can be actually be represented by this subject Fs*T T is over the cycle time which is

equivalent to this total area which corresponds to this making the averaging it should be equal to integration of Fi as a function of t*dt so that makes the average and from here we can find out the what is the average force.

From here we can estimate the average force Fs=this which is corresponds to represent this area sorry to represent this value Fs but we are making simply area balance and we can find out what is the force can be estimated from that. Now if we assume this is the if we but if you want to integrate this thing we know that you should know what is the actual shape of the car would you be assume approximation shape is triangular.

Then we can make the assumption that is the Fs approximately this. So in these cases the average force*the total cycle time t which is averaging over the total cycle time it is average force is simply representation of this over the cycle time the constant force exists that you can say this is the average force which is equal to the if this as a triangle

So what is the area of this triangle? 1/2 of delta t*Fi max area okay delta t max so from here we can find out if s=Fi max*delta t/2t from here we can find out this is the average for t is the time period over the cycle. So this way we can estimate the average speed because the impact all these things is really very random in nature.

So it is rather to look into that what is the maximum force it can achieve and based on that what is the average we can estimate during the effecting in Ultra sonic machining processes. But apart from this things so once we saw that this impacted that impacting on the particle is impacting on the tool but at the same this particle is in contact with the tool material. So there may be some depth or penetration also happens to the tool material because tool is in contact with the particle workpiece and then particle again in contact with the workpiece.

So if we assume that this indentation is happening total indentation can be due to the work piece and can be due to the tool material that indicates the total indentation during the when one particle is impacting on that surface in ultrasonic machining process. So this simple calculation

we can do if we know the own parameters and then we can estimate all these things. Few parameters if you know we can estimate these things.

For example we can assume this average force by the tool. In this case if we know what is the delta t basically what is the delta t or what is the digitalize of the force from 0 to exactly the maximum and what is the maximum amount of this degree if we know the cycle time and all this known to us then we can estimate what is the average force acting during this process?

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During the period Δt, N number of abrasive particles are simultaneously in contact with the workpiece

Force per abrasive particle is $\dfrac{F_{imax}}{N}$

Approximate area of contact per abrasive grain on the work surface

$$\frac{\pi}{4}D^2 = \pi\, d h_w$$

Now during the period delta t N is the number of particles are actually simultaneously in contact with the workpiece and definitely that Fi max is achieved with the application of the simultaneously several N number of particles and of course if we know what is the number of particles abrasive particles are actually in contact with the work piece then per abrasive particular force can be divided this thing.

So per abrasive the particles the calculation of the force is maximum force/number of particles. This is the maximum amount of the force can be exerted by the by single particle. Approximate area of contact per abrasive grain on the workpiece surface. So if we see the abrasive the indentation diameter is =D, indentation diameter by the tool is actually D so such that the area of this projected area is a pi/4 D square and then pi/4 D square we know that D is =Twice square h*d.

So from here we can estimate the pi/4 D square= pi/4*4 hd so that is correspondence to pi dh this is the projected area over which the force is acting. So the maximum stress developed in the workpiece per single particle we can say this is the force per particle maximum force can goes up to this divided by the cross sectional area cross sectional can be estimated that pi dhw.

So that depends the maximum stress can be developed in the workpiece nature. So definitely we should know all these values and Fi max and what is the particle size d and what is the indentation goes to the workpiece all these parameters known to us then we can estimate what is the maximum stress developed in the work piece this way it can be calculated.

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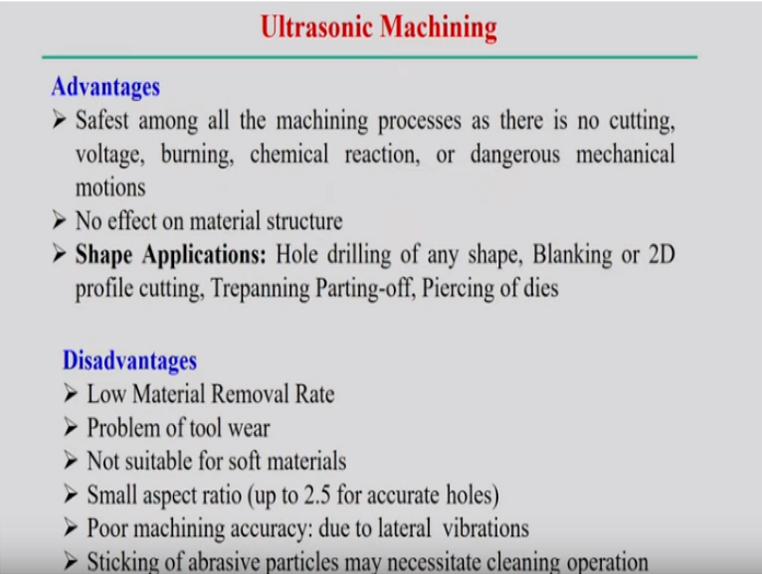
Ultrasonic Machining

Advantages
- Safest among all the machining processes as there is no cutting, voltage, burning, chemical reaction, or dangerous mechanical motions
- No effect on material structure
- **Shape Applications:** Hole drilling of any shape, Blanking or 2D profile cutting, Trepanning Parting-off, Piercing of dies

Disadvantages
- Low Material Removal Rate
- Problem of tool wear
- Not suitable for soft materials
- Small aspect ratio (up to 2.5 for accurate holes)
- Poor machining accuracy: due to lateral vibrations
- Sticking of abrasive particles may necessitate cleaning operation

We look into that Ultrasonic machining overall what is the advantage it is safest among all machining process and there is no cutting, no voltage, burning, chemical reaction does not happen or dangerous mechanical motions not involved in the Ultrasonic machining. So these are it is the very safe process?

No effect on the metal structure because the temperature rises very minimum in this in these cases and dependent type of the same application hole drilling of any shape, Blanking or 2D profile cutting, Treapnning, Parting-off, Piercing of the dies. All these kinds of application we are

possibly using in Ultrasonic machining process. Disadvantage material removal rate is very low so that is a general disadvantage in kind is most of the non-convertible machining process.

Tool wear because we normally use ductile tool is made of ductile material so there must be some amount of the tool that is the one serious problem in Ultrasonic machining process.

If it is a very soft material then it is ultra-sonic machining process is not suitable maybe other non-conventional machining is more suitable. Small aspect ratio 2.5 accurate hole can be used if we cannot take so much more precision or aspect to actually use ultrasonic machining process. Poor machining accuracy a little bit less as compared to the other process due to lateral vibration in these cases so lateral vibration is also important.

So that depends on the what amount of the lateral magnitude it is giving then maybe that sticking of the abrasive particles possible and that may equate that some cleaning operation so of course it depends on what are the size of abrasive particle and distribution of the particles in a sample. So all this kind of disadvantage normally exist in case of ultrasonic machining process.

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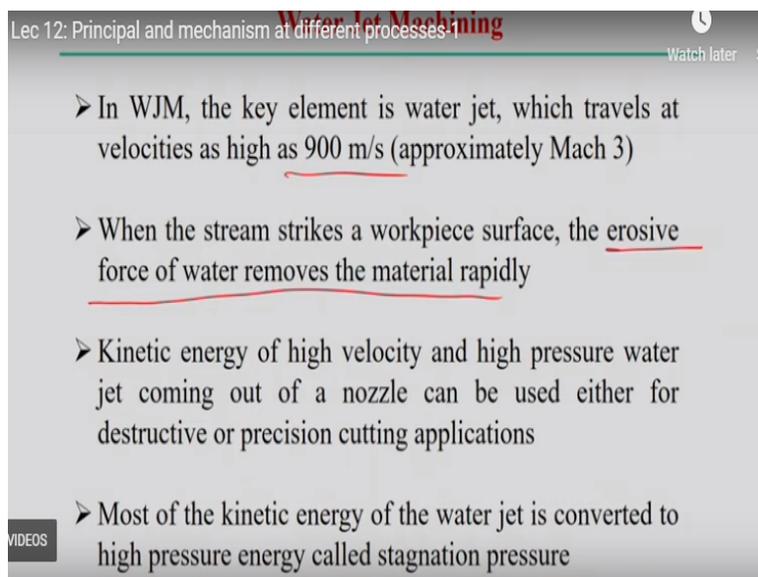

Now we come to that point water jet machining in water jet machining the key element is the water jet so as simple as that create a jet of water that travels can be Mach 3 or around 90 meter

900 meter per second is possible to achieve. So when the stream strikes a work piece it is erosive force of water removes the material rapidly that is the main mechanism water jet machining.

But kinetic the principle if you say the kinetic energy of the high velocity and high pressure water jet coming out from the nozzle and that can utilize for the cutting purposes for a particular material. So most of the kinetic energy of the water jet is basically converted to the high pressure energy and that called the stagnation pressure on which is impacting on the workpiece surface.

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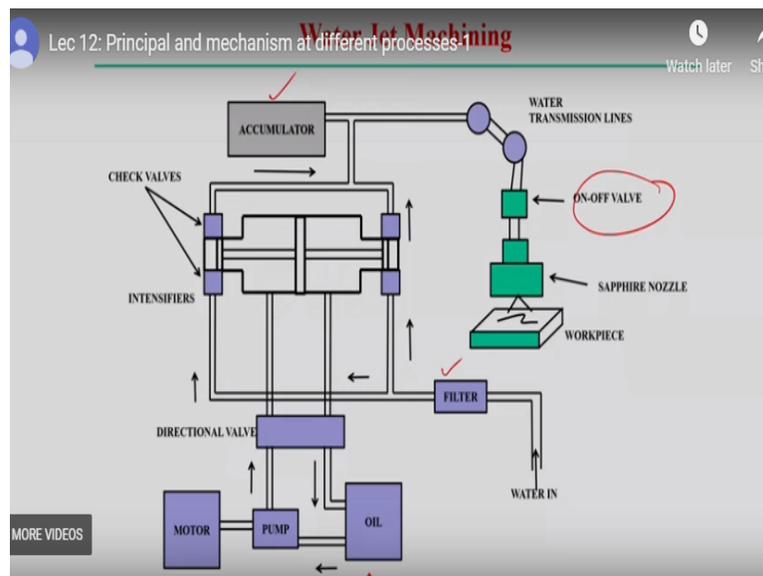
Schematically you can see that accumulator check valves are also there and then there is a two motor and pump. So one is the oil pump is basically a hydraulic oil to clear the pressure high pressure and of course water in and in some cases filter such that we create the very filtered water you can use and we can intensify just increase the pressure of the water and accumulator is also necessary in this case probably.

In this case to supply continuously smooth high pressure water there so it accumulates, accumulates its requirement water transmission line and continuing value on or off we use and from the head and then that directly impact the work piece surface. So schematically it is very looks very simple diagram in case of water jet machining but it involves a lot of parameters to control to get this successfully utilize this process.

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Water Jet Machining

WJM Process Equipment

1. Pumping Unit
2. Cutting Unit
3. Catcher Unit

Pumping Unit:
➤ Electric motor: Heart of the unit to drive oil pump
➤ Oil pump: To pressurize the oil
➤ Intensifier: Acts as a very high pressure pump using low pressure oil to generate high pressure water
➤ Accumulator: Store high pressure water to avoid pulsations so as to produce smooth and uniform water flow at output

Cutting Unit:
➤ Nozzles: to produce high velocity water jet

Catcher Unit:
➤ To minimize noise and to minimize the exposed length of the

Water jet equipment are say pumping unit, cutting unit the catcher unit. So pumping just to pump the pump the oil to pressurise the oil and these things that is the heart of the is just to pressurise the oil and electric motor heart of the unit to drive basically motors drive the oil pump and then oil pump to pressure the oil that intensify act as a high pressure pump using the low pressure to generate the high pressure water.

Basically intensifier high pressure water ad accumulator storage of the high pressure water to avoid the pulsation that means to supply the water it should not be interrupted to avoid any kind of pulses in the accumulator is used. Then cutting unit simply use the nozzle, nozzles from the nozzle that creates the high velocity jet of water and then catcher unit basically suppress the very high noise and minimize the exposed length of the water jet and for the safety purposes.

So catcher is used for safety purposes basically what will happen after the impact of the high jet on the workpiece and catcher unit is used not to spread this water and to fort the safety purpose.
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Water Jet Machining

Mechanism of material removal

➤ Erosion is initiated by micro and macro cracks developed due to propagation of stress waves caused by repetitive impacts of water droplets.

➤ Extend and enlarge the existing cracks

➤ Material removal occurs due to fatigue after a certain number of cycles when equivalent dynamic stress generated by water jet exceeds the endurance limit of the target material

Mechanism of removal simply is Erosion is initiated by formation of micro and macro cracks and for the development of the cracks occurs once due to the propagation of the stress wave and by repetitive impact of the water droplets. So water droplet and this is the typical mechanism propagation of the stress waves but there is a recruitment to initiate the formation of the micro crack first.

Extend and enlarge the crack and the material removal occurs due to the fatigue after a certain number of cycles when equivalent dynamic stress basically generated by the water just exceeds the endurance limit of a particular material. So in this case the material removal by the mechanism of the fatigue. So just by applications the repeated loading to a particular surface once this this covers the endurance limit of a target material then it removes the metal. So that is the mechanism of a waterjet machining process.

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Water Jet Machining **Parametric Analysis**

> Increase in water pressure increases cutting capability of water jet
> Machined depth increases with increase in water pressure for both metals and non-metals.
> A threshold pressure exists below which no cutting takes place
> Cutting ability of jet is most effective when it is directed normal to the work surface
> Depth of groove also decreases with increasing feed rate
> MRR increases with increasing SOD – optimum SOD is necessary
> MRR starts decreasing due to reduction in jet velocity with increasing SOD

Now if you look into different parameters of the water jet machining what are the influence on that we can see that increasing water pressure. Definitely if we increase the water pressure jet pressure will increase and it will jet flow will increase and basically it increases the cutting capability. Depth increases can also be imposed by using the water pressure from both metals and non-metals.

So if we increase the water pressure so definitely the depth of machining also increases and of course there exists some kind of threshold pressure above which it will cut it will guard the it will remove the material from the work piece surface. Cutting ability will be maximum if it is focused on that normal to the work piece surface and of course depth up groove that means depth of groove basically decreases if we increase the Stand- off distance that is between the nozzle exit and work piece material.

So Stand- off distance is very important parameter that actually influence on the metal removal rate at the same time it also influence the position of the geometric shape to produce by any kind of by this kind of water jet. So metal removal rate also decreases due to the reduction of the Stand- off distance increases when the jet imparting only on the work piece surface. In that cases the velocity will decrease if Stand- off distance actually increases.

So definitely Stand- off distance accuracy and the quality of the cut. So some optimum value of the standard distance is required and a metal removal it also increases with increase in the nozzle diameter but we can increase the too much of nozzle and diameter then at the same times there may be the surface quality may also affect. So all these parameters need to optimize by looking into the parametric analysis.

Or just what is the impact of the parameter on the metal removal rate or the accuracy to produce for a particular process.

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Application water jet machining as simply used for soft material mostly and provides the omnidirectional cutting at very high speed clean and sharp cut is possible. No tool wear tool wear tool not tool never dulls or breaks maybe involve for example ultra-sonic machining there is a concern of the tool wear but in these cases we can find out no tool wear.

Dustless environments is required sometime that is the reason in certain cases specifically cutting of the fiberglass. No heat generation no thermal degradation of the workpiece material properties so that is so it is very much advantageous unwanted distortion will not be there. Limitation is to be the expensive equipment maybe higher safety considerations is required due to the high pressure noise and high pressure to handle because sometimes it cross the Mach umber also.

So noise and pressure is very important so the safety concern may be required in these cases. Contaminated water must be treated before disposal. So contaminated because one water may contaminated during this process so it can be water must be treated before use it. Brittle materials this is the common problem brittle materials may crack by using the waterjet machining process the maker because if we look into the mechanism for that it basically removes by the fatigue action and for a particular material using water jet machining is in your process.

So fatigue action maybe a not be difficult action may not be proper it comes clears kind of crack in case of specific for the brittle material.

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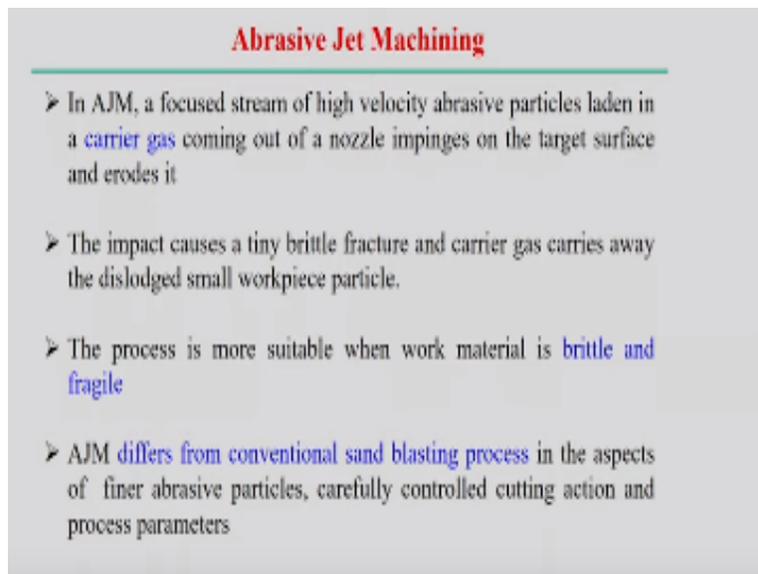
Abrasive Jet Machining

➤ In AJM, a focused stream of high velocity abrasive particles laden in a carrier gas coming out of a nozzle impinges on the target surface and erodes it

➤ The impact causes a tiny brittle fracture and carrier gas carries away the dislodged small workpiece particle.

➤ The process is more suitable when work material is brittle and fragile

➤ AJM differs from conventional sand blasting process in the aspects of finer abrasive particles, carefully controlled cutting action and process parameters

Abrasive jet machining now we will start with the Abrasive jet machining this is another non-conventional machining process in abrasive jet machining a focused stream of high velocity stream is used but that stream along with the gas or any medium gaseous medium normally used. We mixed with the abrasive particles and then clear the jet and that will impact on the surface and removes the material.

So using some kind of carrier gas is required that actually hold the abrasive particles and can create kind of jet. So brittle fracture it normally happens and the carrier gas carries the once the brittle fracture happens the carrier gas also helps to carry the dislodged small workpiece particles with these things.

So this process is very much suitable for brittle material and fragile material Abrasive jet machining but Abrasive jet machining is differs from the sandblasting processes in the aspects of the particle size Abrasive particle size and of course what we can control the different parameters actual process parameters in that way it is different from the blast conventional sandblasting process.

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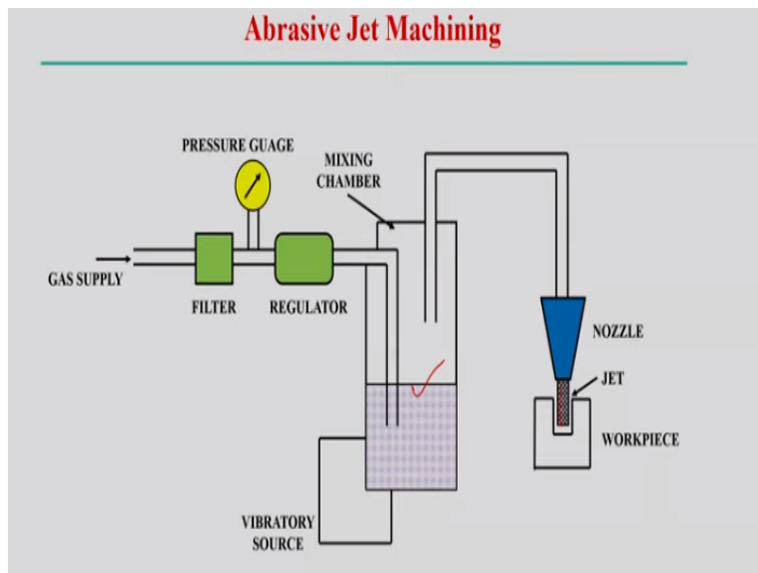
So here we can see the Abrasive jet machining unit a simply vibratory source here mixing chamber the carrier gas and the Abrasive particles are mixed and then processed through the creating the gas supply and filter regulator also there here regulator regulates the gas supply and once it creates it creates the high pressure gas passes to the nozzle and nozzle actually cures the jet and jet will directly in front of the work piece.

So instead of simply water jet machining instead of water here we can use the carrier gas but that carrier gas carry the Abrasive particles.

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Abrasive Jet Machining

Elements: Gas Propulsion System, Metering System, Delivery System

Gas Propulsion System:
➤ To provide steady supply of clean & dry gas used to propel the abrasive particles
➤ Proper filters to avoid water or oil contamination of abrasive powders
➤ Commonly used gas: air, nitrogen and carbon dioxide; oxygen must be avoided presents fire hazards

Metering System:
➤ To inject uniform adjustable flow of abrasive particles into the gas stream
➤ Accomplished by powder hopper that feeds the abrasive particles into a vibrating chamber that causes the powder to be metered uniformly into the jet stream

Elements gas propulsion system, Metering system and Delivery system these are the three basic elements. So gas propulsion system so steady supply of the clean and dry gas used to propel the abrasive particles that to propel the abrasive particles and proper filters to avoid the water oil contamination abrasive particles is also required.

Commonly used gas carrier gas is the nitrogen simply use the air apart from the nitrogen can be used carbon dioxide can also be used but oxygen must be avoided because of the fire hazards. Metering system that adjustable abrasive particles into gas scream this is the powder hopper that feeds from the powdered abrasive particles into a vibratory chamber that actually in vibratory chamber the abrasive particles are mixed with the jet mixed with the carrier gas and then that clears the uniform jet from that point it gives the uniform jet.

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Abrasive Jet Machining

Delivery System: It consists of Nozzles, Masks, and Abrasives

Nozzles:
➤ Continuously in contact with the abrasive particles moving at high speed

Masks:
➤ To control overspray or to produce large holes and intricate details without the nozzle and tracing the shape

Abrasive Collection System:
➤ To maintain the operator's exposure to dusts within permissible limits

Delivery system it creates consists of the Nozzles, Masks and Abrasives and the delivery system and then Nozzles is simply the contact with the abrasive particles and that moving at a very high speed it creates the high velocity jet by using the Nozzles. Mask the role of the mask to protect the unwanted overspray if you do not want to create large holes the intricate shape you to produce.

We can create the mask and that according to the mask the shape can be created and of course control all these things without the nozzle and the tracing of the shape. So not only controlling the tracing of the nozzle and the size of the nozzle and tracing of the shape sizing of the nozzle tracing of the shape apart from by using the additional features by introducing the mask.

We can control the different intricate shape also easily in this process and of course once it is done abrasive collecting system also there and this maintain the operators exposure to dusts within the permissible limit that we simply collect the abrasive system.

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Abrasive Jet Machining

Mechanism of material removal in AJM
- Ductile materials: due to plastic deformation and cutting wear, plastic strain and deformation wear

- Brittle materials: due to indentation rupture, elastic-plastic deformation, critical plastic strain theory, radial cracking and propagation, surface energy criterion

Assumptions
- Abrasive particles are spherical in shape
- Each impact of abrasive produces spherical indentation whose volume equals the volume of the material removed per impact
- For brittle materials at normal impingement of abrasive particles

So Abrasive jet machining mechanism of metal removal in Abrasive jet machining the ductile material sees a plastic definite ductile material plastic deformation occur or cutting wear ,plastic strain and deformation wear is the main mechanism for Abrasive jet machining for brittle materials simply rupture or elastic-plastic deformation, and using the critical plastic theory, radial cracking and propagation, surface energy criteria.

All criteria can be put to decide the or analyse the mechanism of the metal removal Abrasive jet machining but the which is beyond our scope. Applications Abrasive particles assumptions basically if we want to do abrasive jet machining the assumptions is that the Abrasive particles normally assume spherical in shape. Then impact also produce some spherical indentation and equal what is the indentation? It creates the same amount of volume is actually is removed from the surface.

These are the typical assumptions if you want to establish the theory for brittle materials normal impingement of the abrasive particles is the mechanism part we assume the normally impingement of the abrasive particles. Finally rupture due to the spherical indentation caused by the impact of the Abrasive particle is the main mechanism rupture is the main mechanism of the metal removal using the abrasive jet machining process.

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Abrasive Jet Machining

h = Indentation Depth

D = Diameter of indentation

d = Diameter of abrasive particle

$\dot{M}_a$ = Mass flow rate of abrasive particles

η_a = Proportion of abrasive particles effectively participating in the erosion or machining process

ρ_a = Density of abrasive particles

n = Number of abrasive particles striking the work surface $= \dfrac{6\dot{M}_a}{\pi\, d^3 \rho_a}$

v_a = Velocity of the impacting abrasive particle

σ_{fw} = Flow stress of the workpiece material

V = Volume of work material removed per impact of an abrasive particle $= \dfrac{1}{2}\left(\dfrac{1}{6}\pi D^3\right)$

Volumetric MRR $= V\, n\, \eta_a$

Now If you look into the similar calculation and we can perform also. In case of abrasive jet machining if you see that these are the different parameters, Indentation Depth Diameter this diameter of abrasive particles and mass flow rate of the abrasive particles. So similar to what we discuss on the earlier and ultrasonic machining.

We can use some kind of particles and this is the it clears the diameter indent diameter of indentation and h is the Indentation depth and M is the flow rate of the abrasive particles with which we control. We can estimate calculate mass flow rate of the abrasive particles and proportion of the abrasive particle is effectively propagating the erosion or machining actually not all the abrasive particles is actively taking part in the erosive action.

Whether we can say that we can introduce some efficiency term that indicates that introduced the what is the effective amount of the abrasive particles takes part in this process. Density of the abrasive particles then N=number of abrasive particles striking the work surface. So N is the number of particles striking tv is the velocity of the impacting abrasive particle and flow stress of the workpiece material and of course the volume of the work material removal per impact of the abrasive particle.

That we have already we have already discussed that if we look into the volume you estimate the volume of this part then we can find out that. It is half spherical having the diameter d D and

then it is to me is that what is the volume of the metal removal and impact of this particular is this amount. So therefore number of abrasive particles striking though work piece surface. So number of particles striking the work piece surface that we can estimate in the other way also.

So we know the mass flow rate Ma and what is the this what is the volume product?. Volume of the work piece material impacting for abrasive particles which is 1/2 and here 1/6 pi D cube and you can from here we can estimate the relation D is approximately twice h*D. So from here you can find out 1/12 pi D cube 8hd 3/2. So here we can find out hd 3/2 and we can find out that 2/3 pi hd 3/2 can be estimated as the volume or other way you can see this the volume in terms of this equivalent to the volume of the work material removed per impact of the abrasive particles.

This can be estimated like that 2/3 pi hd but other way also we can estimate that number of abrasive particle striking of the work piece what is the volume of the abrasive particles? we can say volume of the abrasive particles this is the volume of the abrasive particles 4/3 pi*1/8 so 1/6 pi d cube is the volume of the abrasive particles what is the mass of the abrasive particles?

One mass of the abrasive particles is the density of the abrasive particle so 1/6 pi d cube/rho a is the mass of the one abrasive particles so d/M.a/ this if you see like this 1/6 pi d cube rho a this indicates the mass of the one single particle. So then mass flow/mass of the one single particle that indicates what is the number of particulars is actually striking to the work piece up surface this we can estimate.

So with these parameters we can find out what is the volumetric metal removal rate that means volume of the V=volume of the material impact per impact of an abrasive particles and n=number of abrasive particles is actually striking on the work piece surface and we multiply it by this fraction maybe that indicates what is the effectively actual number of particles is participating in the machining process.

So basically n*beta a that actually indicates the what is the effective number of particles participating here during this process.
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Abrasive Jet Machining

Considering the indentation caused due impact of a rigid, spherical abrasive particle of diameter d on the work surface at any instant

$$\left(\frac{D}{2}\right)^2 = \left(\frac{d}{2}\right)^2 - \left(\frac{d}{2}-h\right)^2 \quad \Rightarrow D^2 = 4dh - 4h^2$$

Since, h<<d

$$D \approx 2\sqrt{hd}$$

$$MRR = \frac{2}{3}\pi(dh)^{\frac{3}{2}}\frac{6\dot{M}_a}{\pi d^3 \rho_a}\eta_a = 4h^{\frac{3}{2}}\dot{M}_a\frac{\eta_a}{\rho_a d^{\frac{3}{2}}}$$

Indentation depth can be evaluated by equating the kinetic energy of an impacting abrasive particle to the work done in producing an indentation

$$\frac{1}{2}\left(\frac{1}{6}\pi d^3 \rho_a\right)v^2_{\ a} = \sigma_{fw}\left(\frac{\pi}{4}D^2\right)h = \sigma_{fw}dh^2$$

Now here considering the indentation caused due to the impact similar spherical indentation it creates and diameter of the workpiece material at any instant type with a similar calculation we have done D=h2d metal removal rate we can estimate that this is the volume of the this thing we need to say V this indicates the n sorry this is n* this is the effective value of the particle is actually in impact.

So if we do this we can get this expression which is represented in all these parameters. So indentation depth can be evaluated by equating the kinetic energy of the impact of the abrasive particles to the work done in the producing the indentation. So other way also it is possible to find out the indentation depth.

Because here the kinetic energy for indentation we can say that is the we know that kinetic energy 1/2 of mass *velocity square which is what is the amount of the work done in other way also the force rate the force rate value that area that force* it impact up to the distance h. So force*distance that work done or energy equivalent to that make this equal. Force rate*energy and then from here this is=dh square. So from here we can react different way.

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Abrasive Jet Machining

$$h = dv_a \sqrt{\frac{\pi \rho_a}{12 \sigma_{f_w}}}$$

$$MRR = 1.46 \frac{\eta_a}{\sigma_{wf}^{0.75} \rho_a^{0.25}} \dot{M}_a v_a^{1.5}$$

> **Parametric Analysis**
> Finer grains are less irregular in shape hence possess lesser cutting ability also have more tendency to stick together and choke the nozzle
> Abrasive mass flow rate increases, the MRR also increases as more abrasive become available for cutting
> MRR increases with increasing gas pressure at a decreasing rate and tends to saturate beyond a certain value
> Carrier gas attains the maximum velocity at the nozzle exit and starts decreasing with increasing SOD
> Accuracy of the cut decreases as the SOD increases due to spreading of the jet

So that h can be represented like this h= in terms of d particle velocity and this. Finally metal removal rate if you replace in terms of h then we can find out the metal removal rate then maybe this constant comes from the here but it depends on the this way the parametric value of all this parameters. Efficiency mass flow rate, velocity and density of the particle and the force rate value so all this way we can estimate what is the metal removal rate in case Abrasive jet machining.

But parametric analysis indicates that a few significant points that finer grains are less irregular so that is may have lesser cutting ability may be reduced or sticking to get stuck with the stick together with the work piece material That is the one problem finer grain size the abrasive flow rate increases the metal removal definitely abrasive flow rate increases the metal removal rate also increases and more abrasive becomes available for the cutting action.

Metal can also be increases if we increase the gas pressure so gas pressure increases when increasing the gas pressure but the increment of the gas pressure decreasing rate, rate of increments would be low and that tends to saturate beyond a certain value. So we can increase the gas pressure up to a certain extent to increase the metal removal rate.

So carrier gas actually attains the maximum velocity at the end of the nozzle exit and start decreasing with the Stand- off distance.So Stand- off distance would be optimum way to

accuracy of the cut depends on the Stand- off distance which is in increase due to spreading of the jet. So Stand- off distance increases jet will spread so that actually deteriorate to the surface probably.

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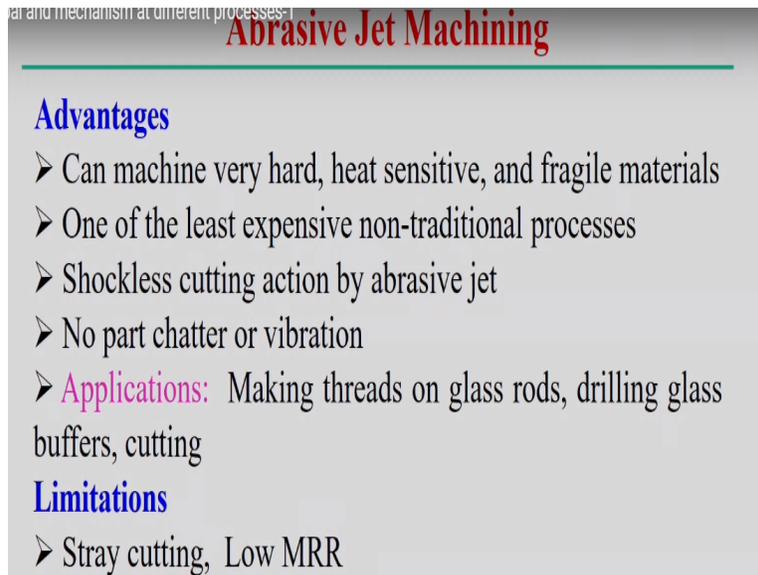
So advantages very hard, heat sensitive and fragile materials can be used in case of Abrasive jet machining and one of the least expensive non-traditional processes and shockless cutting action is possible by abrasive jet which was difficult in case of probably in that water jet machining. No part chatter of vibration Application we can find out glass rod, drilling glass, cutting all these cases we can found the application of the abrasive jet machining.

Limitation is there low metal removal rate , Taper can be put but it depends in the shape of the Stand- off distance and short nozzle Stand- off distance used for cutting and particles can be imbed into the work piece. So that is a main difficulty and it depends on the what is the size and distribution to the particles are normally fine particles chances of the embedded to the work piece during this process.