

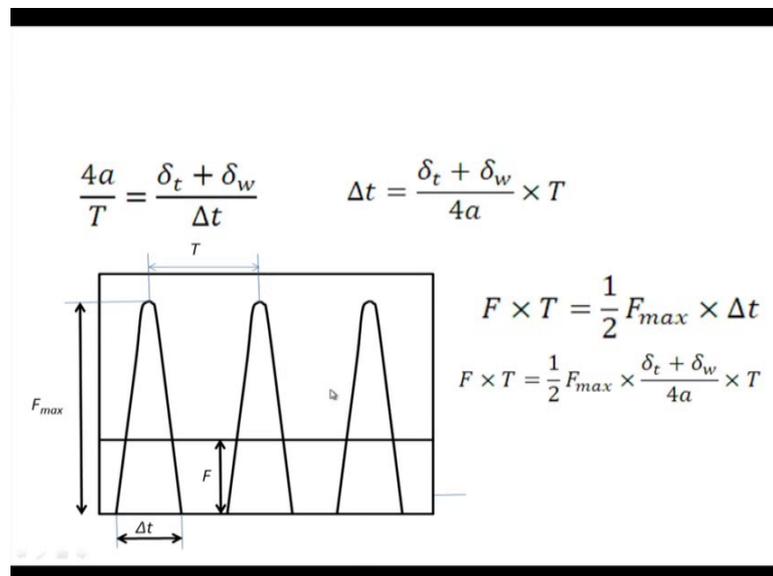
Non-traditional abrasive machining process: Ultrasonic, Abrasive jet and abrasive water jet machining
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Lecture - 03
Ultrasonic Machining (Contd.)

Welcome to the third lecture in the lecture series on Non-traditional Abrasive Machining Methods Ultrasonic Machine Abrasive Jet Machining and Abrasive Water Jet Machining. So, at the end of the second lecture we have we had been discussing about the impact of abrasives due to the hammering action of the horn on top of them. And this was the particular figure that we had been discussing.

And we had we had discussed that with this was the time axis and this was the force axis and while this designates the constant static load that we are applying that we means we are pressing the 2 things the tool and the work piece with a constant static force.

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But at certain points in time the force is shooting up due to the impacts of the horn contacting the abrasive and driving the abrasive into the work piece and the tool surfaces; forces rising and then forces falling off as the horn is receding due to the vibration.

So, these are the places where the force blows up. And we had found out a relation in which the force is ultimately found to be this particular maximum force. These are instantaneous force values with time as in the maximum force. By assuming this to be a triangle we have found out it is area and within one particular cycle we have equated force into time that is impulse we have equated the impulses. And from that obtain the relation that F_{max} is equal to 8 into static force into the amplitude divided by the sum of the indentations on the tool and the work piece surface.

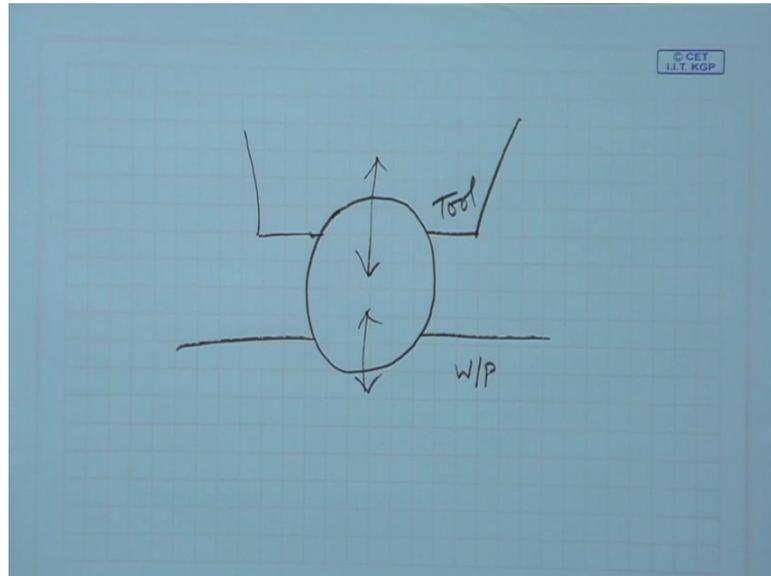
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$$F_{max} = \frac{8 \times F \times a}{\delta_t + \delta_w}$$

- Now, the indentations on the tool face and the work piece surface are created by the same force. And both have undergone plastic deformation.
- Hence, $\sigma_t \times \frac{\pi}{4} \times D_t^2 = \sigma_w \times \frac{\pi}{4} \times D_w^2$
- or $\sigma_t \times 4 \times \delta_t \times d_1 = \sigma_w \times 4 \times \delta_w \times d_1$
- Or $\frac{\delta_t}{\delta_w} = \frac{\sigma_w}{\sigma_t} = \frac{H_w}{H_t}$

Let us now try to derive a relation between the indentation on the tool surface and the indentation on the work piece surface. How do we calculate them? So, let us have a look. First of all we will be I think you will agree with me if I say that; if you look at this body.

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If this be the tool and this be the work piece at the same point in time, the same force must be occurring between these 2 and these 2 if we consider (Refer Time: 03:29) not very high So that other forces are not existing. And therefore, the same force is creating the indentation on the tools side and the indentation on the work piece side. Therefore, if that be so, we can quickly say that the projected area $\pi d t$; that means, on the tools side the indentation diameter. So, the projected area is $\pi d t$ multiplied by the flow stress on the tools since it is undergoing plastic deformation. Flow stress for the tool material this is the expression or the force.

Since this force we are considering to be equal to the force on the work piece side. So, it must be equal to flow stress of the work piece because the work piece also undergoing plastic deformation multiplied by the projected area this time $d w$. So, if we have established that it essentially means that these 2 will be equal πd will cancel out from both sides.

And therefore, $D t$ can be replaced by once again that relation pythagorean relation that we had derived. So, from that my replacing big $D t$ we are getting Δt into d and Δw into d . $D d$ cancels this 4 cancels out and we ultimately have a relation that Δt by Δw is equal to σ_t by σ_w by σ_t and that is equal to hardness of work piece by hardness of tool.

That means we are saying when a body is plastically deforming the flow stress can also be considered to be an expression of hardness (Refer Time: 05:33). So, we will use them interchangeably in this particular analysis. So, if we have delta w common here if it is taken common we will have 1 plus delta t by delta w. And therefore, we can replace it by delta sigma w by sigma t.

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The slide contains the following mathematical derivations:

- So,
- $$F_{max} = \frac{8 \times F \times a}{\delta_w (1 + (\sigma_w / \sigma_t))} = \frac{8 \times F \times a}{\delta (1 + \lambda)}$$
- However,
- $$F_{max} = n \times \frac{\pi}{4} D^2 \times \sigma_w = \frac{c \times A \times d}{\frac{\pi}{6} d^3} \times \frac{\pi}{4} D^2 \times \sigma_w =$$

$$\frac{3 \times c \times A \times D^2}{2 \times d^2} \sigma_w = \frac{3 \times c \times A \times 4 \times \delta \times d_1}{2 \times d^2} \sigma_w = \frac{3 \times c \times A \times 4 \times \delta \times \mu \times d^2}{2 \times d^2} \sigma_w$$
- $$= 6 \times c \times A \times \delta \times \mu \times \sigma_w = \frac{8 \times F \times a}{\delta (1 + \lambda)}$$
- So,
$$\delta^2 = \frac{8 \cdot F \cdot a}{6 \cdot c \cdot A \cdot \mu \cdot \sigma_w (1 + \lambda)}$$

So, let us see that. So, we have taken delta w common and therefore, delta t by delta w we are replacing by sigma w by sigma t as per previous calculation. And after that we are replacing this particular expression sigma w by sigma t or H w by H t pi lambda. So, lambda is equal to sigma w by sigma t as is obvious ok.

It is just a simplification of term So that it becomes easier to handle; however, you might still ask what have we by the way delta w has been replaced by delta we have drop that subscript w, because once that subscript t is gone it is not necessary for us to continue with w. We can well drop it and therefore, we have dropped, but we should still remember that it pertains to the deformation on the work piece. So, you might ask me that what is all this leading us to: we still do not have an expression of F max. Do we? Do I know delta? That means the indentation on the work piece. No, at least I cannot find it out analytically. So, let us proceed with the analysis. We try to analyze it from another angle. What we say is the F max force must be the total force which is coming due to a number of abrasive particles.

Therefore, we say that it must be equal to total number of abrasive particles which are active under the tools surface let us call it n . N number of abrasives offer this small force and therefore, it is ended up altogether to create F_{max} . What is this force? This force is simply σ_w or H_w whichever you would prefer to use here σ_w multiplied by the projected area. So, there is nothing wrong here, this is the small amount of force for abrasive and this is the total number of abrasives.

So, therefore, we are you know multiplying n to get the total force coming from these individual abrasives. Now n has to be estimated, what is the value of n ? How many abrasives are actively participating in the you know material removal at one point in time? For that we make use of the expression of concentration. Concentration is volume by volume fraction of abrasives inside the abrasive water slurring.

What is this mean? Whenever you are working on the ultrasonic machine we will make some gross or broad based estimation. You might ask your student that how much abrasives are you using in this experiment. You will say why is that important you will say because I have to make an estimate of the concentration of abrasives because it is it is very much an expression used in the analysis. So, he will say that I actually there was one bucket of water and to that I added say half a bucket of abrasives.

So, you will say fine that is the estimation; that means, in 3 parts of slurry there is only one part of abrasive So that the concentration comes out to be one third. And therefore, we make an estimate now of the concentration from volume considerations. So, if the cross section or the or the tool be a the tool surface has a cross section of A , big A small a is the amplitude.

Therefore we can say concentration must be equal to the total volume under the tool multiplied by the concentration multiplied by the concentration. This is the total volume of abrasive divided by the volume of each and every abrasive and you will get the number of abrasives. So, concentration multiplied by area of tool multiplied by one abrasive grit diameter; that means, we are assuming that there is a monolayer; that means, a single layer of abrasives possible under the tool surface. So, if that be So the total volume under the tool which is housing or accommodating the abrasives is a into d multiplied by abrasive concentration is c , c into a into d must be giving you the volume of abrasive represent under the tool, that is good? Now if we divided by the volume of

abrasives and volume of an individual abrasive will get the number of abrasives. So, we divided by $4 \times \frac{3}{4} \pi r^3$, you are not using r , but we are using d and therefore, it comes out to be $\frac{\pi}{6} D^3$.

$\frac{\pi}{6} D^3$ So that is creative at the bottom. So, $c \times d$ divided by $\frac{\pi}{6} D^3$, that gives us the expression of number of abrasives participating in the machining process at a particular point in time. So, we make some simplifications in that because you will see that there is d at the top, d at the D^3 at the bottom and therefore, you will have d^2 at the bottom. So, you will find here we have d at the top D^3 at the bottom.

So, that we have d^2 at the bottom we have large d^2 here and therefore, we are having it here once again σ_w is occurring here. And all the other terms are you know 3 comes here c comes here a comes here and what is this $4 \times d \times \Delta$ oh that is coming from d^2 . D^2 is simplified input here and $2 d^2$ was already existing and therefore, we can still remove the expression of $d \times d$ we are replacing by μ into d^2 .

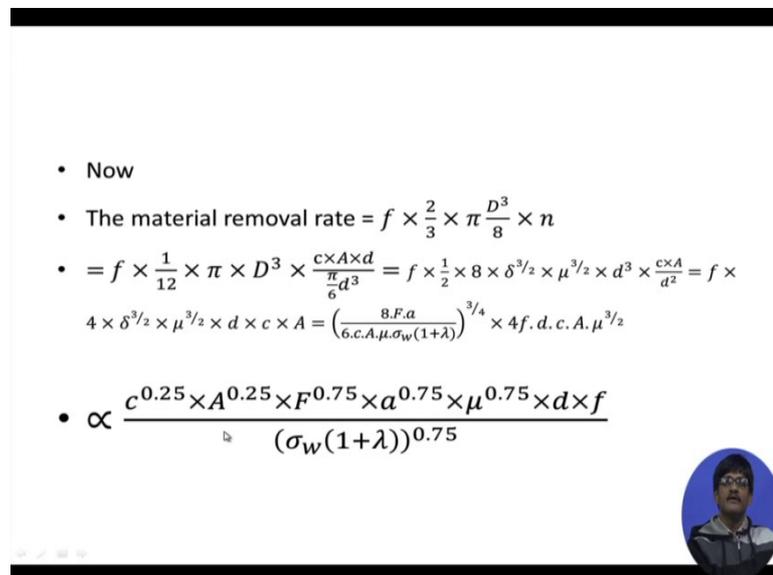
μ into d^2 please remember d_1 is the low diameter and d is the grit diameter and they are related as $d_1 = \mu d^2$ and therefore, we have replace that. So, all these you know variables are crunched whatever can we canceled out it is cancelled d^2 cleanly cancels out with the d^2 at the bottom. And therefore, we have c coming here a coming here Δ coming here μ coming here σ_w coming here and 6 you are not very much bothered about these constants because ultimately you will see that we will be dropping them and expressing the relation as a proportional into relation. So, anyway this is F_{max} remember F_{max} we have now found out from the considerations of concentration. And we have all we had already found out the expression of x as F_{max} here and therefore, we equate the tool.

When we equate the tool we get an expression of Δ^2 , why? Because Δ was occurring here and Δ has occurred already there and therefore, by cross multiplication we consider Δ^2 is equal to this. Let us inspect what we have here you have Δ^2 ; that means, deformation or indentation square is equal to $8 \times f$; that means, static force into amplitude divided by $6 \times$ concentration square cross section of tool $\mu \sigma_w \times 1 + \lambda$ that is good. We have now what an expression of Δ . You

might say if I give you in the machining conditions can you find out find out delta for me? Yes, F is known say F is 10 Newton's a is the magnitude given to be say how much say 40 microns and say c is given concentration is 0.2 a is given to be a particular cross sectional value. And mu is given say one sigma w is provided for a particular material lambda is also provided.

Lambda is hardness of you know if you remember hardness of work piece by hardness of tool. So, delta square can now be estimated ones the delta square can be estimated we can easily find out the metal removed.

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- Now
- The material removal rate = $f \times \frac{2}{3} \times \pi \frac{D^3}{8} \times n$
- = $f \times \frac{1}{12} \times \pi \times D^3 \times \frac{c \times A \times d}{\frac{\pi}{6} d^3} = f \times \frac{1}{2} \times 8 \times \delta^{3/2} \times \mu^{3/2} \times d^3 \times \frac{c \times A}{d^2} = f \times 4 \times \delta^{3/2} \times \mu^{3/2} \times d \times c \times A = \left(\frac{8.F.a}{6.c.A.\mu.\sigma_w(1+\lambda)} \right)^{3/4} \times 4f.d.c.A.\mu^{3/2}$
- $\propto \frac{c^{0.25} \times A^{0.25} \times F^{0.75} \times a^{0.75} \times \mu^{0.75} \times d \times f}{(\sigma_w(1+\lambda))^{0.75}}$

Because materials remove we have already assumed to be hemispherical chunks with delta indentation and large d as there you know edge diameter. So, material removal rate is a first of all coming from every impact it is equal to instead of 4 by 3 pi r pi D cube by 8 it is 2 by 3 2 by 3 pi D cube by 8, that is good. Into the number of abrasives which are taking part into the frequency because so many times per second this material is getting removed. And therefore, by simplification we get F into 1 by 12 into pi into D cube and n we have already computed it to be if you remember c into a into d divided by pi by 6 into D cube. This I am just you know importing from the previous derivation and therefore, after that we start crunching the numbers; that means, that we replace them by known values and then be ultimately simplify and find out what we get.

For example D^3 can be replaced by 8 into δ to the power $3/2$ δ to the power $3/2$ into μ to the power $3/2$ into D^3 . You might say when you get that from well, if you remembered d is equal to twice root over of δ into $d \delta$ into d^1 . So, if D^3 is taken we will have δ to the power $3/2$ and d^1 to the power $3/2$. And from d^1 we bring in d and therefore, it becomes D^3 . And from the concentration we have c into a etcetera I am not you know working term by term now because I am sure once you got the hang of it, it is very simple calculation where you have to stay alert not (Refer Time: 17:35) any careless mistake and definitely you will arrive at the correct answer.

So, after that it becomes equal to now let us collect start collecting the coefficients and you will find that c to the power 0.25 is going to occur. How So? Let us quickly trackback. We have from the end term we have from the end term one c occurring. So, that is one full c . And what is the other source of c ? The other source of c is coming from the expression of δ . Remember we had found out an expression of δ^2 now we are replacing it in this particular expression. And we have got c to the power three-fourth in the denominator. So, c at the top and c to the power three-fourth at the bottom gives us c to the power 0.25 or c^2 the power $1/4$ th at the denominator at the numerator.

So, in the same way I am now not going to go into each and every term, but we will get c to the power 0.25 , area to the power 0.25 ; static force to the power 0.75 amplitude to the power 0.75 μ to the power 0.75 . Diameter of the grid, frequency of vibration divided by the flow stress or the hardness of the work piece surface work is material sorry, $\lambda^1 + \lambda$ to the power 0.75 in the denominator. So, this is the expression of MRR. Or rather MRR is proportional to this particular expression. So, ultimately we can say we have got a good estimation of the terms to which MRR is going to be proportional. And we will be able to utilize this expression to good effect in order to derive material removal rates, ok.

So now let us go on to next one. So, we have derive an expression for material removal rate.

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MCQ

- For making a circular section hole of diameter 5 mm in Mild steel plate of thickness 10 mm, the most appropriate process would be
 - - die sinking EDM
 - none of the others
 - drilling with cw laser
 - Ultrasonic drilling with abrasives
 - Ultrasonic drilling without abrasives
 - Conventional drilling
 - drilling with pulsed laser

Let us try all some MCQs before proceeding onto harder problems. Let us see, for making a circular section hole. So, I am I am basically have making a hole which has a circular cross section of diameter 5 millimeters in mild steel plate. Mild still means that the carbon percentage is around 0.2 percent perhaps, mild steel plate of thickness 10 millimeters.

The most appropriate process would be die sinking EDM, none of the others, drilling with continuous wave laser. Ultrasonic drilling with abrasives ultrasonic drilling without abrasives, conventional drilling and drilling with pulsed laser; first of all die sinking EDM would should we used that well it can be used there is no harm in using it, but we have to first find out whether there is any other competing process which proves to be more convenient. None of the others means that using that none of them will be applicable no this is; obviously, not correct.

Drilling with continuous wave laser what is continuous wave continuous wave means that it is not pulsed, but the level of power of the laser output power level of the laser remains constant with time do we use that well let us see let us go ahead with the other options, ultrasonic drilling with abrasives (Refer Time: 21:44) this can definitely be used definitely for let us see, but mind you as this is mild steel it will be a ductile material. And you would not be getting very high material removal rate with mild steel if you use ultrasonic drilling. Ultrasonic drilling without abrasives well then you will be out with I

mean you will be without abrasives and therefore, your material removal rate will not be high provided it will cut at all is not specified how this drilling is being done. But without abrasives it will be at a disadvantage, whether it is it is it is you know some other kind of a material removal method is being employed or not it is not clear.

It might be that you would not be you look it at all if you are using conventional ultrasonic drill without abrasive. Now comes conventional drilling; that means, using and conventional drill tool and trying to machine the material last world drilling with pulse laser just like you have come continuous wave laser, you can have pulsed laser also. Now what is this pulsed laser?

Now in case of a pulsed laser it allows you know vapour and projectile material droplet us metal droplet us which are melted to come out of the hole during the times during which the laser is off, if the laser is continuously on material will continuously get produced and if you difficult to remove it from the blind hole. So, pulsed laser is better than continuous wave laser for drilling, but whether it is appropriate here or not that we have to now find out. The answer to this is conventional drilling and why So? Because conventional drilling is very you know in expensive compared to these processes. And it gives you good geometry geometrical accuracy and surface finish.

So, why go for the other methods which might be costing you more which might not be giving you well defined geometry which might not be giving you good surface finish? Why go for them if you have conventional? Means applicable use a conventional means here and that is the answer.

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- Glass can be machined by
- - EDM but not by (USM, ECM)
 - ECM but not by (USM, EDM)
 - None of the others
 - USM but not by (ECM, EDM)

Glass can be machined by EDM and not by USM or ECM. ECM glass can be machined by ECM, but not by USM EDM none of the others; USM, but not by ECM or EDM. So, glass being a non conductive material, it cannot be machined by EDM or ECM. And therefore, the last option is correct it says that glass can be machined by USM and not by ECM or EDM.

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- - The “horn” in the USM process is a tool that is commonly tapered towards the machining end so that
 -
 - Micromachining tools can be held
 - Higher pressure can be applied on work surface for the same static load
 - None of the others
 - Weight of the machine is less and hence vibration would not be damped out
- 

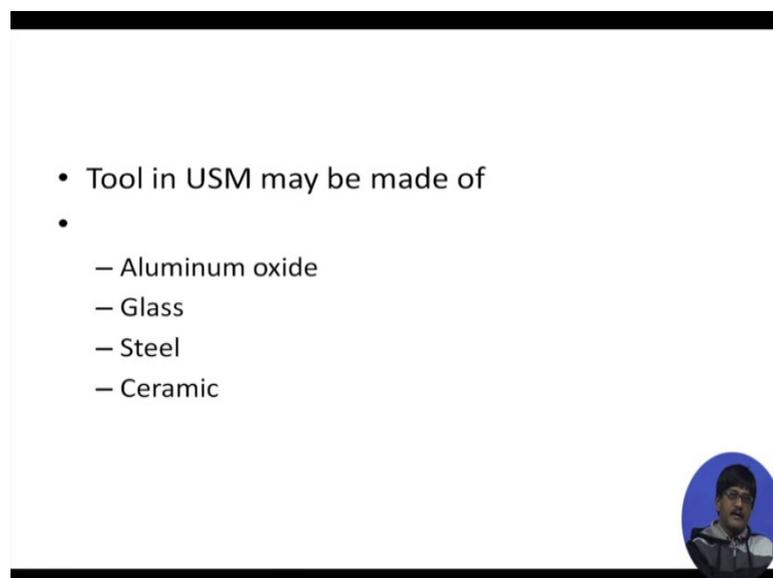
The horn in the USM process is a tool that is commonly tapered towards the machining end So that micromachining tools can be held, higher pressure can be applied on the

work surface for the same static load. None of the others and weight of the machine is less than hence vibration would not be damped out. So, first of all, if you want to hold micromachining tools the tools themselves can be small, why does the horn have to be small in that case? So, the first option is not correct.

Higher pressures can be applied for the same static load, once again the horn can well have a large diameter all through, but the tool it is holding at the end that only can be less in diameter and that should take care of what is mean claimed. So, the diameter does not necessarily you know have to be less for these cases. Weight of the machine is less and vibration would not be damped out.

This is also not you know not the reason for which it is commonly tapered. It is commonly tapered for a completely different reason. That is amplification of the amplitude. The amplitude is magnified at the tool end of the horn due to it is tapered shape.

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- Tool in USM may be made of
- - Aluminum oxide
 - Glass
 - Steel
 - Ceramic

Tool in USM may be made of aluminium oxide glass steel ceramic. Tool here means that the at the end of the horn there is something put or attached which is you know having the shape conjugate shape of the final shape that you want, and it should not take up much damage from USM. If it is glass or ceramic definitely it will take up damage which is aluminium oxide then also it will take up damage because aluminium oxide is you know reasonably brittle. So, steel must be the answer, it has to be made of steel So that it

itself will not take up much damage being basically a ductile material and it will not crack.

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- Q1
- USM (ultrasonic machining) is carried out on work material A and work material B. The tool is made of material C. The material removal rate for machining material A with tool material C is M_{AC} and that for machining material B with tool material C is M_{BC} . If the hardness values of A, B and C are 7000, 5000 and 1000 (all in N/mm²) respectively, find the ratio $\frac{M_{AC}}{M_{BC}}$ [5]
- Given, MRR in case of ultrasonic machining is given by

$$MRR \propto \frac{c^{1/4} F^{3/4} a_o^{3/4} A^{1/4} d_g f}{\sigma_w^{3/4} (1 + \lambda)^{3/4}} \mu^{3/4}$$

- F = Static force, A = Area of cross section of tool, Abrasive grit diameter = d_g , amplitude of vibration = a_o , Work piece material fracture strength = Its hardness = σ_w , Tool material fracture strength = Its hardness = σ_t , c = abrasive slurry concentration v/v , $\lambda = \sigma_w/\sigma_t$, $\mu = 1$ Take hardness = fracture strength

[FL] let us have a I do not think we have time enough to discuss this problem, but you can (Refer Time: 28:11) as a take home problem let say quickly what it says ultrasonic machining when you here; I think I should mention that in the final exam and in the assignments we will only have multiple choice questions, So that all these you know these elaborate problems that we are going to discuss in the lectures ultimately they will come in the form of multiple choice questions. But we will discuss the process in the lectures.

So, ultrasonic machining is carried out on a work material a and work material b. The tool is made of a work material c the material removal rate for machining material a with tool material c is MAC and that for machining material b with tool material c is MBC Is a hardness values of a b and c are 7000, 5000 and 1000 in Newton's per millimeter square respectively. Find the ratio of MAC by MBC given material removal rate in case of ultrasonic machine is given by this expression which you we have already derived. So, we have no issues with that expression where all these things are derived let us have a quick look at these F is the static force A is the area of cross section abrasive grit diameter is d g.

So, they are using d_g instead of d that is all right. Amplitude of vibration is a 0. So, they are using a 0 for amplitude of vibration work piece material fracture strength equal to it is hardness equal to σ_w , tool material fracture strength it is better to use flow strength in this case. Flow strength equal to it is hardness equal to σ_t . C is equal to abrasive slurry concentration and λ is defined as σ_w by σ_t and take hardness equal to fracture it should be flow strength.

So, we will discuss the answer to this one in our next lecture.

Thank you very much.