Non-traditional abrasive machining process: Ultrasonic, Abrasive jet and abrasive water jet machining
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Lecture – 11
AJM (Abrasive Jet Machining)

Welcome viewers to the 11th lecture of our online course on Non-Traditional Abrasive Machining Methods and today we are going to start with Abrasive Jet Machining or AJM.

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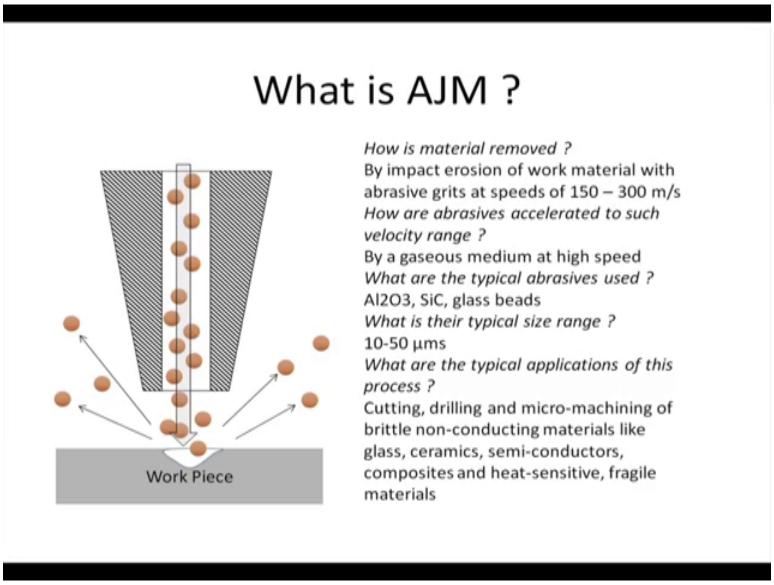

What is abrasive jet machining? Abrasive jet machining is in which this nozzle through which abrasive particles; that means abrasive grids are carried in a high velocity gas stream to impinge on a work piece surface and remove material by impacts. Why is the material removed is because whenever a brittle, essentially brittle materials are generally preferred as a work material, in these cases that means if we have brittle materials, abrasive jet machining will be very much you know usefully applicable.

So, if we have a brittle material impacted by such abrasives, what are these abrasives? They are generally you know some particular metallic ceramics which have very high not only in metallic, but there can be ceramics in general which have very high hard disc, essentially high rigidity and they have high melting temperature also, but main thing is that they have very high hardness and they have very high form stability and therefore, when they hit the work piece surface, they generally cause fractures due to impact and when these fractures accumulate, they are going to produce damage which we refer to as material removal. We can create you know grooves and cuts etcetera or drills. I mean holes etcetera by this method in such hard brittle and non-conductive materials conductive also.

For conductive materials, there are other competing processes, but for hard brittle non-conducting processes, non-conducting materials, this process is almost you know without any competition. So, let us have a quick look at the method how is material removed by impact erosion of work material with abrasive grit at the speeds of 150 to 300 meters per second. Some people even considered to be 100 to 300 meters per second. Our abrasive particle accelerated through velocity range. This is by a gaseous medium at high speed.

What are the typical abrasives used? The typical abrasives used are aluminum oxide, silicon, carbide, glass, beads etcetera. What is the typical size range? They are in the size range of 10 to 50 microns. What are the typical applications of this process? It can be used for cutting, drilling, micro-machining of brittle non-conducting materials like glass, ceramics, semiconductors composites, heat sensitive fragile materials etcetera.

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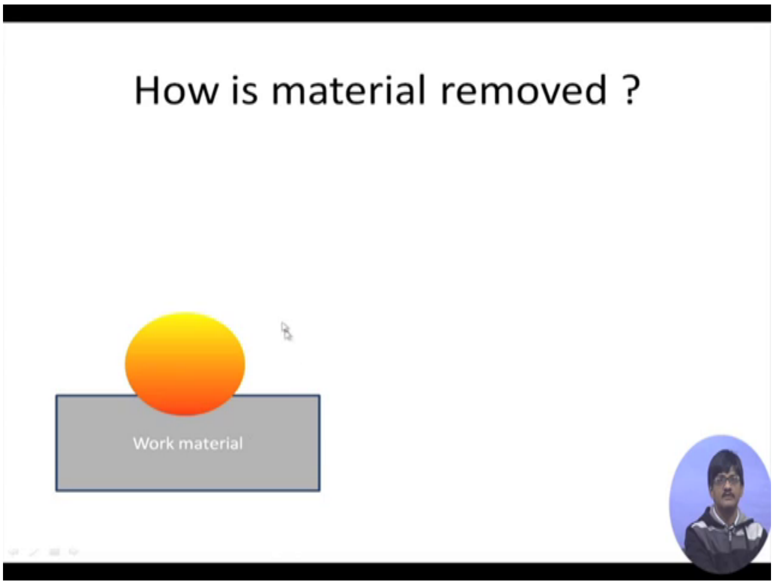

How is material removed, let us have a quick look. So, this is the abrasive and this is the work material. Just one such abrasive is being shown and it goes and impacts the work material.

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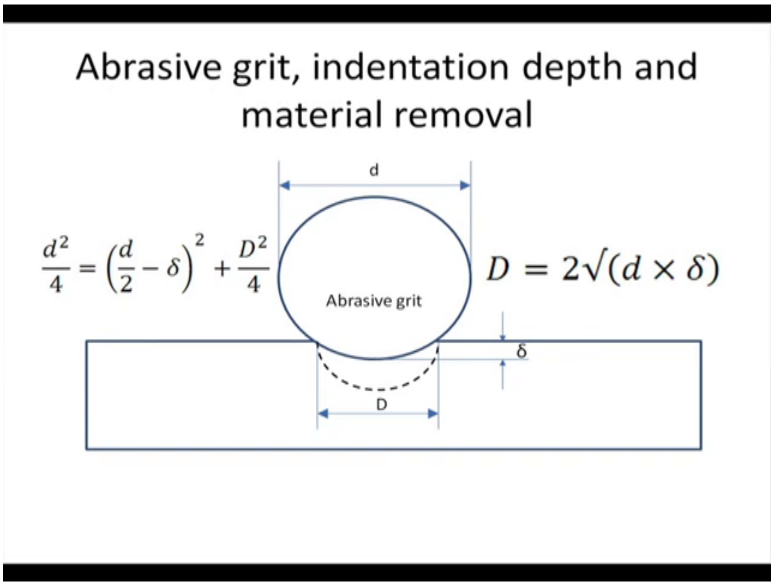

We are conversant with this particular geometrical you know figure in which you know this is what happens and we have already done this particular calculation. I just remind you what we are talking about. This is the abrasive grit which is hit the work piece material and this dotted line shows the line of fracture by virtue of which a hemispherical chunk of material is getting removed. The relation that we had you know derived was that delta being the indentation and large D being you know diameter of the damaged circular portion at the top of the damage creator, ok.

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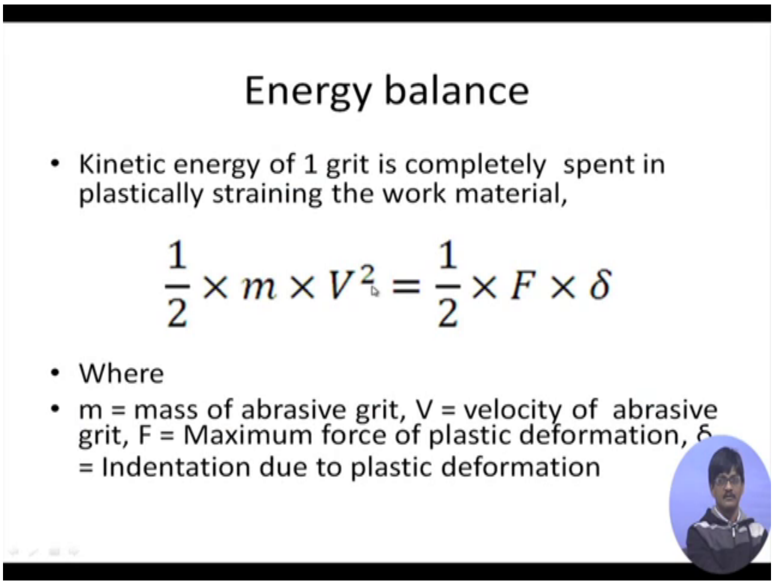

If this is the diameter and if the diameter of the abrasive grit be D in that case can have pythagoras relation.

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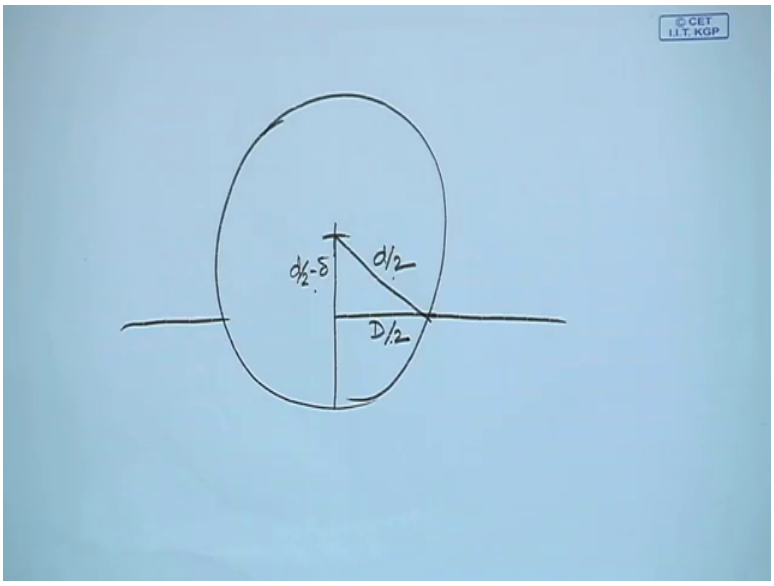

Just a one minute. We can have algebra of quick figure to show you what I am talking about. If you look at it here, this is d by 2. This is d by 2 and this is d by 2 minus delta. So, this pair plus this pair must be equal to this pair. So, returning back to the figure, we see hypotenuse square is equal to the square of the other two sides and from here if we neglect delta square to be too small, we will ultimately arrive at this particular relation. I am not doing this relation. I am sure you can do it. So, d square, sorry d will be equal to 2 into root over d multiplied by delta. This we have already done. Before it is done in all books, text books etcetera and you also can well easily derive it.

So, let us proceed what we see is that a grit is coming and hitting the work piece surface and the grit is mind you at very high speed. So, what we see is that when it hits the work piece surface, how does the material get removed and here we assume that the complete kinetic energy of the grit is converted into plastic strain energy of the work material.

So, if the work material is plastically deformed, the work done which is at you know due to this plastic straining can be expressed as half into F into delta, where F is the maximum force of plastic deformation which is occurring and delta is the indentation due to plastic deformation since maximum force is not existing all the time. So, we take half of it as the average over the particular time of deformation. So, we have the energy carried by the abrasive particle being half m V square, where m is the mass of the abrasive grit and V is the velocity of the abrasive grit. So, half m V square must be equal to half into F delta force into displacement is going to work done and here the mean force of half F has been considered. So, with this expression we will have m into V square is equal to F into delta.

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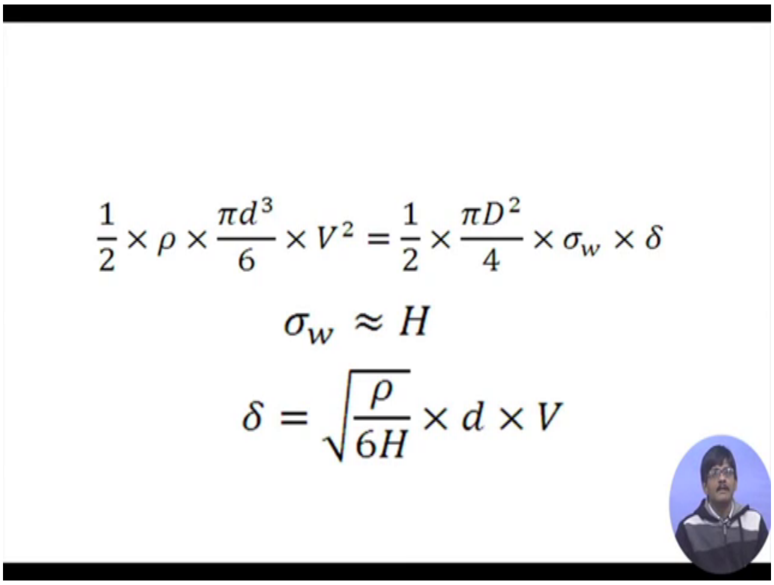

Now, if we break down mass and write it as density into volume, we can quickly write considering that the; I mean assuming that this abrasive grit is a perfect sphere of diameter d. We can write half into density into volume 4 by 3 pi r square equal to pi by 6 into d cube multiplied by velocity square. What is the value of the velocity? I will say I do not know. Whatever velocity is being set, I do not know it. So, I am using a variable value equal to half into the projected area of you know of the contact of the abrasive particle with the work piece in the ultimate situation projected area.

So, how much is the projected area, the contact area, its projection is on the x y plane. So, that is why we are written pi by 4 into D square, d being large D multiplied by stress. Now, why are we doing this? We are saying that since plastic deformation is taking place, the force which is existing the maximum force which is existing and thus creating you know ultimate creator, it must be equal to the flow stress of the work piece equal to sigma w multiplied by the projected area. So, that is why we are replacing maximum force by the plastic flow, flow stress multiplied by the projected area and delta was already there once.

We are interchangeably using flow stress of the work piece material with the hardness of the work piece material, then the same things to us. [FL]. Now, if you know simplify this and find out, we will find that this gives us a relation like this.

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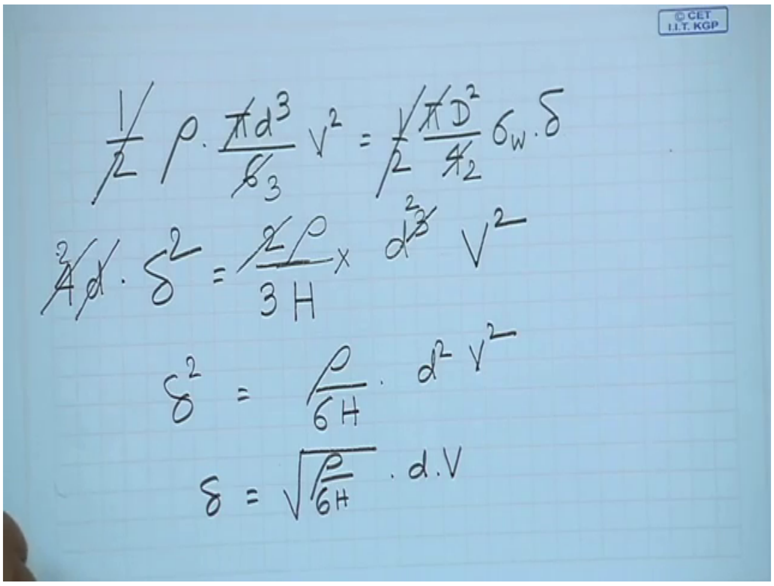

Let us have a quick look how we process this. So, we can write half into rho into pi d cube divided by 6 into V square equal to half into pi D square divided by 4 into sigma w into delta. Here you will notice I will scratch this out and this goes away as well and what else. This will be 3 and this one is 2 and therefore, I can write delta equal to that is starting from here, delta equal to this one goes down. So, I can write H instead of sigma w. This one remains here sigma write rho and what else was there? I have 3 here by 3 multiplied by 2, ok.

What is let see if V square was here? V square now comes D square. Now, what is D square going to do? D square will be going and settling down as this is tricky because it has a delta inside. D square will be equal to 4D into delta. That means, delta square and therefore, we will have to consider there is 1d cube here. So, if 1 d cube is here and D square 4 d, this will cancel and this will become to the power 2. We have retained d cube and we have cancelled it out, so that delta square becomes this one cancels 2 delta square becomes equal to rho by 6H. This 2 goes down, 6H into D square into V square which means delta can be written as root over rho by 6H into d into V. That is all.

So, that is the relation. Coming back to you know screen, you will find that is the relation that we were suppose to get delta is equal. That means, the indentation is related to d larger. The grit diameter moving with the indentation which is common sense; higher the velocity, more will be proportionally high will be the indentation and of course, it is related to the density and the hardness density of the abrasive particle and hardness of the work material once we have arrived at this particular expression of delta.

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- MRR = MRR due to one impact × Number of impacts per second
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- Number of impacts per second = mass flow rate of abrasives / mass of one abrasive
-
- = Mass flow rate of abrasives / (volume of one abrasive × density of one abrasive)

$$= \dot{M} \Big/ \left(\frac{\pi}{6} d^3 \times \rho\right)$$

Let us proceed on to find out an expression of MRR. MRR we know we can express it this way. It is equal to MRR due to one impact. That means, material removed due to one impact multiplied by the number of impacts per second. This should be material removed, not MRR because the rate is coming here number of impacts per second.

So, material removed due to one impact multiplied by number of impacts per second is equal to MRR. How do we find out the number of impacts per second? What are we given in the machine? Generally we are provided this information say the abrasive mass flow rate will be provided to us. What kind of values will it have? See 2 grams per minute, 3 grams per minute like that. So, that way abrasive mass flow rates suppose it is M dot. If it is M dot, it means as M dot grams per minute is being used. So, how can we find out the number of abrasives present in such abrasive stream? What we do is, we come back to the stream number of impacts per second. If we come back to the screen, have a look at that number of impacts per second is equal to mass flow rate of abrasive that is M dot divided by mass of one abrasive. So, that will give me the number of abrasives in that particular stream. That is good.

So, mass flow rate of abrasive divided by volume of one abrasive into density of one abrasive equal to M dot divided by once again that 4 by 4 pi r cube that we have expressed in diameter will give us pi by 6 into d cube multiplied by density. So, mass of one abrasive particle is here, it divides the total mass flow rate of abrasives and therefore, this gives us the number of impact like abrasives in the stream and we assumed that 100 percent efficiency is there of impact. We can say this very term is the number of impacts. Have you understood that?

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$$= \frac{\pi}{12} D^3 \times \dot{M} \Big/ \left(\frac{\pi}{6} d^3 \times \rho\right) = \frac{(4\times d\times\delta)^{3/2}}{2\times d^3\times\rho} \times \dot{M}$$

$$\frac{(4\times d\times \delta)^{3/2}}{2\times d^3\times\rho}\times\dot{M} = \frac{4^{1.5}}{2}\times\frac{\left(\sqrt{\frac{\rho}{6H}}\times d\times V\right)^{3/2}}{\rho\times d^{3/2}}\times\dot{M}$$

$$= 1.04\times\frac{\dot{M} . V^{3/2}}{\rho^{1/4} . H^{3/4}}$$

Let us now quickly calculate this out. How do we calculate it? We say that pi by 12 into D cube, what is pi by 12 into D cube? Pi by 12 into D cube happens to be the hemispherical chunk which is removed per impact multiplied by the number of impacts. I have just copied down the number of impacts which we deduce just now here. That is good. So, what do we have here? We have number of impacts I have kept unchanged. What else is there? This pi will cancel out, this 12 and 6 will leave behind 2 here. So, there is 2 here and D cube I have imported from here directly. You write d cube and rho. Here also I have directly imported it here and this d cube which is here for that, I have written 4 in d into delta, ok.

Why? It is because this is the expression of square, d square. So, I have taken to the power half. So, that I have taken d here now, but d cube is there. So, I have take it to the power 3. So, first from d square to d is done by this 2 and from d to d cube is done by this particular power. So, this is equal to you know intermediate expression between this one and the final answer. So, if we simplify this since d to the power 3 is at the bottom and d to the power 3 by 2 is at the top, therefore they will interact and formed d to the power 3 by 2. That is good and what else? What are the other terms that you have to think about? We have to think about you know what, about delta here, right.

So, delta we have derived the expression of delta a few minutes back and I have directly put in the value of delta here. Remember rho by 6H into d into V, therefore what we notice is that we had got already d to the power 3 by 2 and we are getting d to the power 3 by 2 here and therefore, this d to the power 3 by 2 cancels out and the funny thing is the final expression does not have the expression. I mean the contribution from diameter of grit at all is extremely interesting, but it is true the final expression of MRR in abrasive jet machining will not contain any you know expression of d. That means, abrasive grit is not affected by that.

Secondly what do we have here? We have V to the power 3 by 2. So, out it comes directly V to the power 3 by 2. What about rho? We have contribution of rho from here which is you know 3 to the power 3 by 2 and again another root sign. So, it will be 3 to the power 3 by 4 and here we have rho only. So, naturally at the bottom we will have rho to the power one-fourth, 3 to the power 4 on the top and one at the bottom. So, we have rho to the power one-fourth n dot was n dot from the beginning to the end and thus, it remains and hardness is present here.

So, its power is 3 and due to this root by 4, 3 by four. So, H to the power 3 by 4 and all these you know constants, they can just be crunched together and found out and it comes to be 1.04. So, it is simple. Material removal rate of an abrasive jet machining process can be expressed simply by this particular expression 1.04 into M dot into V to the power 3 by 3 into rho to the power one-fourth into H to the power three-fourth ok.

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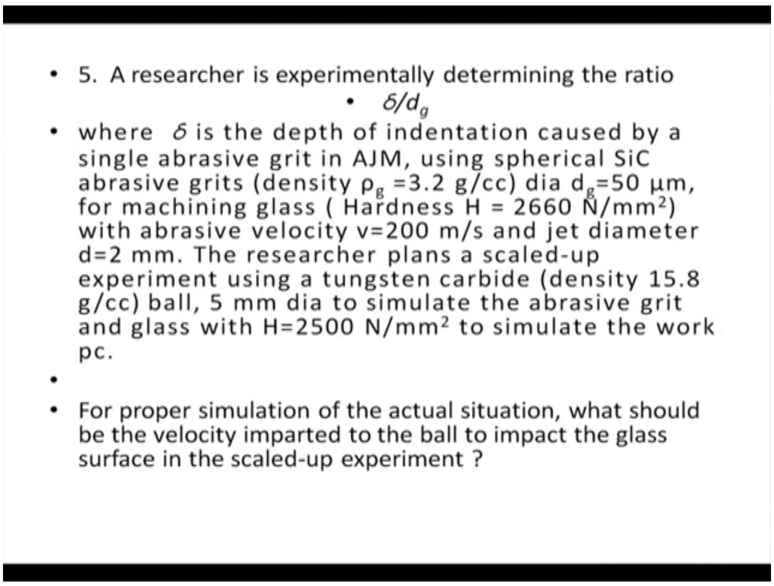

So, we will use this expression to solve a number of problems. Let us have a look at them. A researcher is experimentally determining the ratio delta by d g. What is delta by d g? Delta is the indentation depth and d g is the diameter of the grits. So, what you might say what arr they trying to do the researcher says that for any material I mean this is back up information that is there should be a y always associated with a particular solution of a problem. If we are trying to solve a problem, we have to first of all see whether it is meaningful to do it or we are doing something just for fun or just some abstract academic interest.

So, a researcher is experimentally determining a ratio delta by d g. What can it perhaps represent if it is a soft material delta will be higher and if it is a very hard material, delta will be lower and therefore, you can say that I can measure the hardness this way or you can say I can give you an estimate how much its machinability be when you are considering the case of abrasive jet machining. So, you say give me the material, give me the abrasive powder type. That means, what diameter the average diameter it has and give me delta by d g, I will tell you how much machinability this particular material will have. This is the reason for which is possibly trying to find out this value.

So, what is the problem let me measure it, but the problem is this d g is so small that if you fire an abrasive particle towards a source and towards the target and try to estimate how much damage it has made, it is extremely problematic due to the size affect and how do you control essentially one abrasive particle make it create a damage etcetera.

So, the general procedure is if you are really interested in doing something like that, fire an abrasive jet towards you know towards a target for some time, calculate the number of hits by the method that we have done and then, divide the total cumulative damage by the total number of particles which we have hit the body during that time and that we find out an average delta by d, but the researcher is not satisfied with this. He will say maybe half the interacts are not taking place. Maybe one is hitting on top of the other and therefore, he is saying that it will not represent the true picture. So, he is planning for a laboratory level experiment, where he will say I will get very accurate pictures what is going that is good.

So, what he is done is, he is selecting the case of abrasive silicon grits. The density 3.2 grams per cc diameter 50 microns and the material to be glass with hardness of 2660

Newton's per millimeter square; if the abrasive velocity equal to 200 meters per second and jet diameter d equal to 2 millimeters, but he was not doing the experiment with this one. He is doing the experiment with a scaled up model where he is using a tungsten carbide ball with a density of 15.8 grams per cc and the diameter of the ball is 5 millimeters.

So, instead of 50 microns which can hardly be you know seen by the naked eye, you are using 5 millimeter diameter tungsten carbide ball. What is he doing? He is taking as the work material a glass with hardness 2550 Newton's per millimeter square. So, he will drop this ball and this single ball will cause a damage of significant dimensions which he can measure. So, he will say I will do this experiment with a single ball and get a very accurate representation of indentation at the lab level on large work piece. I can measure it and get an estimate. There will be no overlapping of results of a number of grits in this case.

So, that is quite well planned experiment, but the problem is a proper situation of the actual situation is what should be the velocity imparted to the ball to impact the glass surface in the scaled up experiment. Now, what does that mean? It means that everything is different. The diameter of the ball is different the density of the ball is different. Instead of density to be 3.2 grams per cc, it is 15 grams per cc. Instead of diameter 50 microns, it is 5 microns, 5 millimeters much higher and the glass also is instead of 2660, it is equal to 2550.

So, how can we possibly simulate? The answer to this is since he is finding out delta by d g, he is trying to find out delta by d g might be in that case let us see what value the velocity should have. So, that delta by d g comes out the same. In both cases, we will take such a velocity such that the delta by d g will come out to be the same in you know theoretical case.

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$$\frac{\delta}{d_g} = \sqrt{\frac{\rho}{6H}}V$$

$$\frac{\delta_1}{d_{g_1}} = \frac{\delta_2}{d_{g_2}} \qquad \sqrt{\frac{\rho_1}{6H_1}}V_1 = \sqrt{\frac{\rho_2}{6H_2}}V_2$$

$$\sqrt{\frac{3.2}{6 \times 2500}} \times 200 = \sqrt{\frac{15.8}{6 \times 2660}}V_2$$

Hence V = 87.5 m/s

If you have to drop the ball from a height to attain this velocity, $h = \frac{87.25^2}{2 \times 10}$

= 380 meters.

As well as the experimental case delta by d g delta 1 by d g 1 should be equal to delta 2 by d g 2. We know that delta is delta by d g is equal to rho by 6H into V. This D is simply taken to be this side. So, if this is the expression for delta by d g, let us put the values of the first case here and the second case here and say that if they are equal, what should be V2? So, rho 1 in case of the first case is 3.2 grams per cc. Just one more minute. Rho 1 is 3.2 grams per cc by 6H. H is equal to 2500 and just a moment. Am I correct in this one, the values?

The first case, the hardness is 2660 Newton’s per meter square. Friends, this will be 2660, ok and this is 200.

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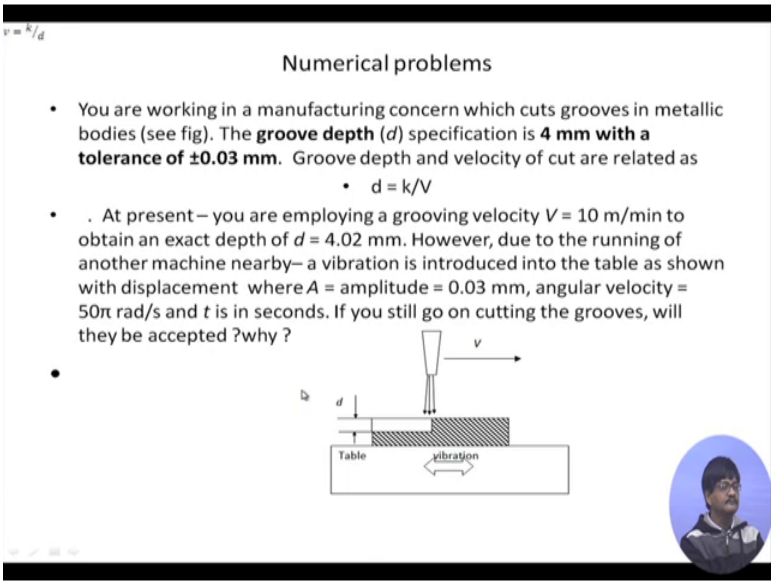

The initial velocity and this is 15.8 by 6 into 2550 should be equal to V2. Shall we try out in excel quickly? That is a good idea. Let us do that. I will quickly get an excel working. Just hold on. That is it. Let us first derive what we have written. Please have a look here first.

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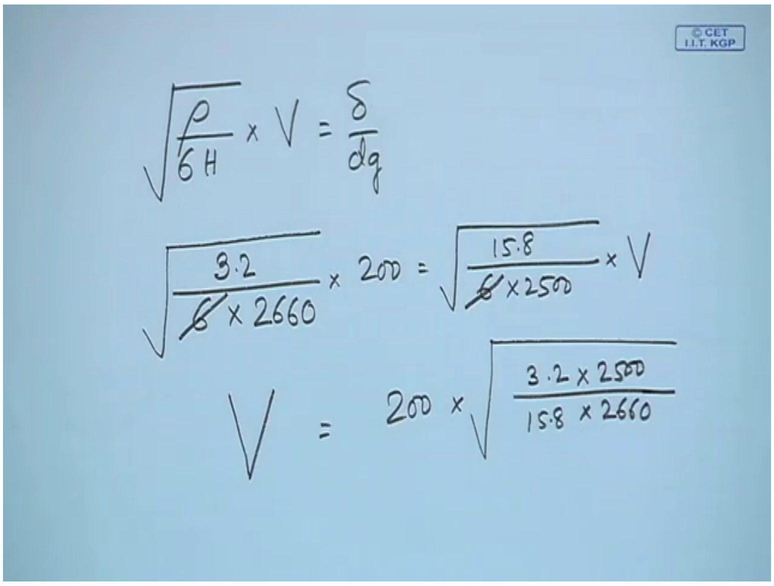

So, we have rho by 6H root over into V. This one is the expression of delta by d g. So, this will be 3.2 divided by 6 into 2660 root over multiplied by 200 equal to root over 15.8 divided by 6 into 2500 into V. Let us do some cancellation. This goes out, this goes out and therefore, V will be equal to 200 multiplied by root over 3.2 by 15.8 multiplied by you know 2500 into 2660.

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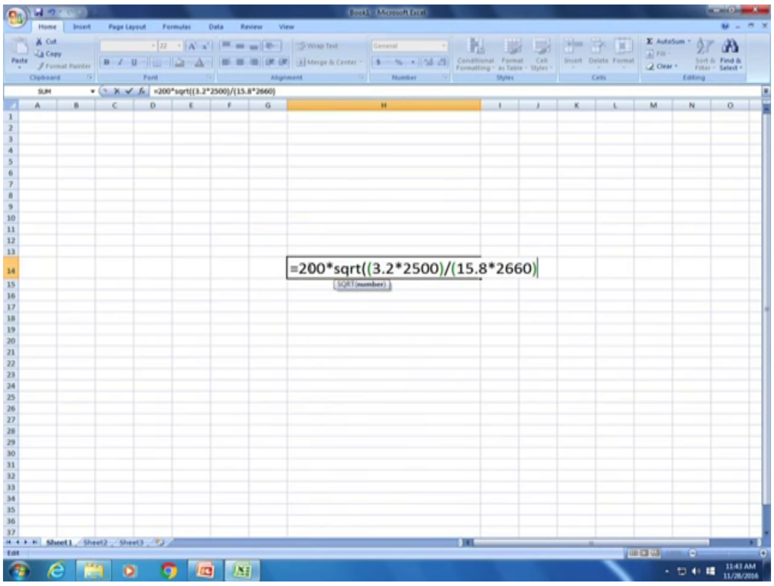

Let us solve this. So, V have equal to 200 multiplied by square root of bracket. Let us take another bracket for the numerator. What is the numerator? It is 3.2 multiplied by 2500. Is that correct? Yes, divided by bracket 15.8 multiplied by 2660 bracket close. It seems to be all right. Let us proceed and get the answer such that you must say let some bracket they are giving an answer of let recheck it. What have they done? They are given a bracket here. That is good square root.

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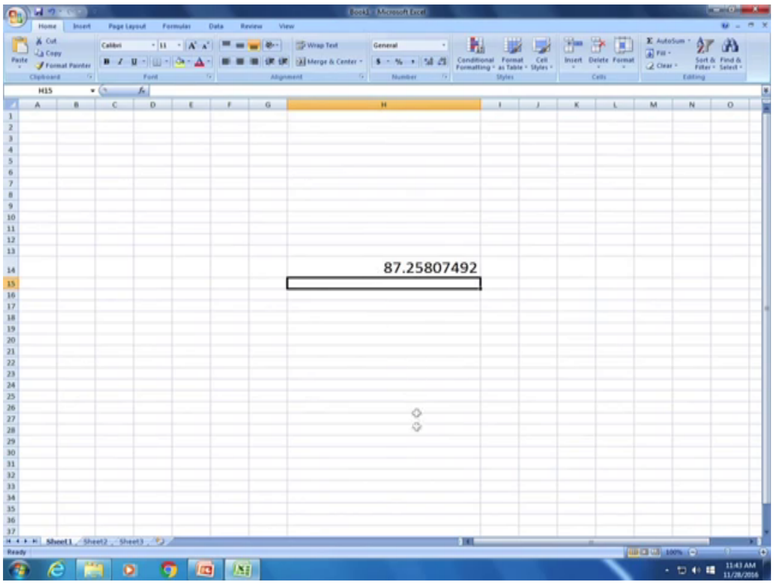

So, the answer is this way. Velocity comes out to be 87.25. If we come back here and have a look at the previous problem that we were discussing, this was 87.5. So, this is the answer. If you drop this ball with a velocity of 87.5 meters per second on the experimental glass, in that case the delta by d g that we will obtain experimentally will be exactly equal to the delta by d g in the theoretical case and that way in a scaled up experiment, we will be able to estimate delta by d g. Last of all if you drop it from a particular height, what should be this height? It will be 380 meters. So, if you drop it from 380 meters, it will develop 87.5 meters per second.

I hope this was easy to understand, not very difficult and interesting also. So, next day we will continue with this discussion.

Thank you very much.