

Introduction to Mechanical Micro Machining
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Lecture - 16
Difference between macro and micro machining (Contd.)

Good morning everybody and welcome again to our course on introduction to mechanical micromachining. In the last class, we have seen some of the differences between the macro machining and the micro machining in terms of if you are machining a alloy material or if you want to machine any isotropic material.

So, we have seen that there are different type of mechanism by which material is being removed in macro machining and the micro machining. And then we started new topic in that that how the specific energy is different in macro machining or the conventional machining and the micro machining. So, let us continue that topic on specific cutting energy.

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Specific cutting energy
The energy consumed in removing a unit volume of material.

Specific cutting energy in case of orthogonal cutting:

$$u = \frac{F_c V}{bh_c V} = \frac{F_c}{bh_c}$$

Small $h_c \rightarrow$ small F_c

Cheng, Huo (2013) Micro-Cutting: Fundamentals and Applications, WILEY

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And so that we have seen here that this is a single point cutting tool. And this cutting tool is moving in right to left direction. And this is the uncut chip thickness, this is the cutting velocity, this is the width of the chip, and this is the force F_c which is required to penetrate these tool into the work piece material. So, how you can define the specific cutting energy, the energy consume in removing a unit volume of materials, so that is

called specific cutting energy. And in orthogonal case this is a equation by which we can actually define or we can give a equation that is F_c into V , so that will give you the energy requirement. And this is the b is the width, h_c is the uncut chip thickness and V is the velocity cutting velocity. So, here you will get a millimetre cube by minute or second whatever you are getting. Then this V will go away and then your equation is shorten to the F_c divided by b into h_c . So, this is the shorter version of your equation for cut a specific cutting energy.

Now, what is important here that when your h_c increases, now we will just let us discuss about these two parameters and our force requirement. Now, you considered that we have two situations. So, this is the cutting tool, and this is your h_c , this is the one situation. And let us give one more situation on the same graph that your h_c is bigger now. So, this is your new h_c correct. So, now what is understanding of this thing that if you reduce your h_c , your first requirement is reduced, because now you do not to remove more material, is the thickness of this uncut chip thickness increases that is h_c then you have to apply more forces.

So, this is very general idea, and there is no need to apply any theory here. So, this is how it should work. So, smaller the h_c , smaller is the F_c force that is in normal machining operation, wherever we do conventional drilling machine, milling operation, lathe turning operation or the drilling operation.

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Specific cutting energy

Cutting force (F_c) does not tend to continue to decrease as the uncut chip thickness (h_c) reduces.

$u = \frac{F_c V}{b h_c V} = \frac{F_c}{b h_c}$

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Now, what is the problem here? So, this is what is happening. So, this is the same equation here, and we have given the same thing here. The cutting force F_c force does not tend to continue to decrease as the uncut chip thickness h_c reduces. Now, what is the problem here, now if you see up to this thing correct, now this both the things this is moving F_c . So, if you reduce your F_c , then your cutting force was continuously reducing and this was the specific cutting energy.

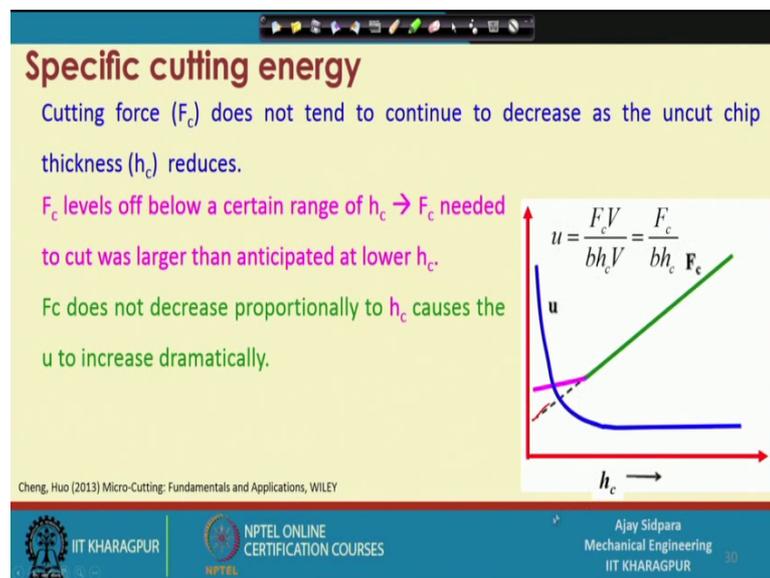
Now, if you see this equation h_c is in the denominator and F_c is in numerator. And if you continue this thing, if you see this particular line this is a your specific cutting energy is constant it is not changing, it is not higher, not or lower also because this both the things are moving simultaneous. If you are reducing h_c , if you are reducing h_c your force will also reduces. So, both the things are balance with each other so that is why you are u is not changing with respect to changing in the specific uncut chip thickness up to a certain level.

But now if you see that once it crosses one particular limit now what happened that this balance is not maintained now. Now, this is the yellow pink colour line. So, by particular this strength that if your h_c is reducing, F_c also reduce then it should follow this base this line, then again your on specific cutting energy will be a straight line, but that is not the case here, because now here what is the problem that it is not happening like that, and that is creating a problem in the specific cutting energy. Now, you can see that now your force F_c is on the higher side, basically it should lower side to balance this equation, but that is not happening in the micro cutting, so that is the problem.

So, now, what is happening now let us write that equation again here u equal to F_c divided by $b h_c$ correct. So, now, mostly we know that this is in micron size. So, let us consider 100 micron. And F_c force is also in 1 to 2 Newton depending on the material and your other process parameter settings. So, now consider this is in micron and this is in denominator. So, when it will go on the upside at that time it will be very very high. So, if you consider this thing in a metre scale then it will be the 10^{-6} , and when it will go in the upper side that will become 10^6 correct, so that is what is going to happen in the micro scale. Because when you reduced this to a very very small level, these things will reduce.

Now we know that this balance is now reduces. So, now, your F_c is actually increases correct so that is what is happening once you cross a one particular limit of reduction of the uncut chip thickness. And your h_c also reduces, but h_c is denominator, so now if you consider this is going from 100 to 10 micron, so basically it is 10 raise to minus 6 meter correct. So, now, u will be F_c into 10 raise to 6 divided by b into 10 correct. So, these become positive. And we know that we are reducing this continuously which is in denominator, but your F_c is not reducing it is going high and high because of this particular thing. So, now ultimately your u will be extremely high and that is why now you can see the trend of this u it is very very sharp when it is moving in the this particular region. So, now, this particular tend you can understand that how it is being.

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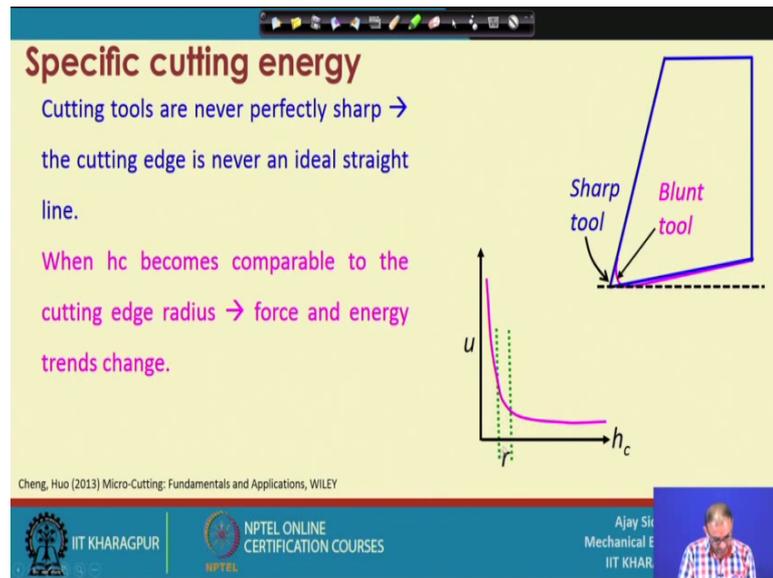


So, now what we are talking about uncut chip thickness in this particular range, so now we can think about the perceiving cutting energy of the grinding because when you do grinding operation you chip thickness is very, very small compared to your turning operation and the milling operation. So, now this increase of this uncut chip specific cutting energies actually directly connected with the uncut chip thickness reduction with respect to reduction in the cutting force and that is what is happening here.

Now, F_c levels off below a certain range of h_c that is what is happening here, an F_c needed to cut was larger than the anticipated at the lower h_c value. So, we are following this particular line, but this line is not followed when you do machining at a micro scale.

And F_c does not decrease proportionally to h_c causes u to increase dramatically. So, because now we know that our denominator is in micron, so it will be extremely high when we multiply this thing with the very very high amount of force is comparatively here in this case. So, your u will be definitely higher side in the micromachining.

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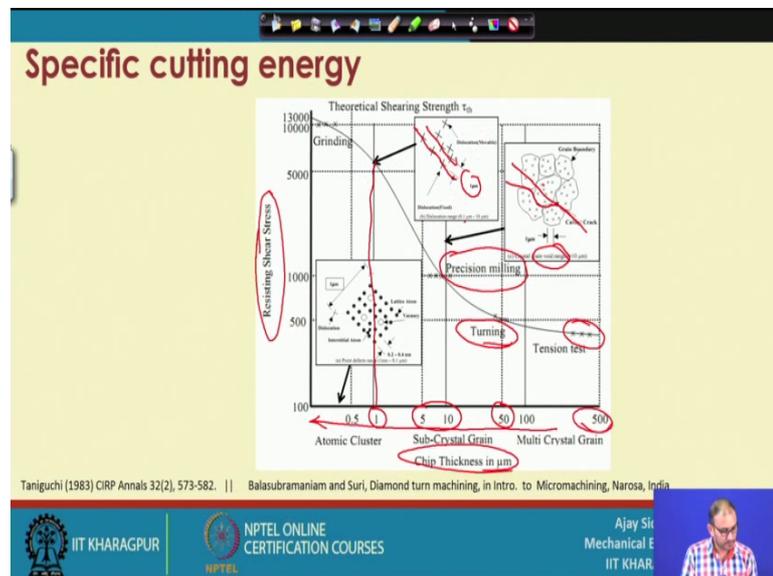
So, what other what other way we can define those particular thing that whenever we see the cutting tool our cutting tool we cons considered something like this. So, we consider that our cutting edge is very very sharp here in this particular case, and it is penetrating very very perfectly and smoothly into the material. So, you can easily get a chip out of it correct, but now we know that cutting tool are never perfectly stuff. So, this is a schematic diagram, but whatever way you can see this particular thing at a microscopic level, you always get a round image. And that again you have to scale with respect to the uncut chip thing how much material you want to remove and cutting is never a ideal straight line.

Now, if you see this is the sharp tool and this is the actual tool. Now, if you consider this is the thing because now our uncut chip thickness is at micro level. So, we have to look our cutting tool also at the same magnification of the same scale. So, this is what is the actual condition of your cutting tool correct. So, this is consider as a blunt tool. Now, it depends on this blunt tool how much it will penetrate into the material, and how it will remove the material in form of chip.

So, when h_c becomes comparable to the cutting-edge radius. Now, consider this is our cutting edge radius R_c . So, this is the cutting edge radius R_c . And now you can consider your chip is also here. So, this is your h_c correct. So, now, both the things you consider almost same so at that time force and energy trends changes. So, in this particular case that is what is happening. So, you are not talking about the what is the sharpness of the cutting tool when you cut in the micro scale or conventional machining, but this sharpness again play important role when we do same cutting at the micro scale.

So, now this is the again trended. So, this is the h_c now and this is the u in this direction. And this is the range of r . Now, if you consider the this is up to which range that your u are was continuously maintaining its range without any change, but as soon as it is moving in this particular range, where the h_c is matching with this thing. So, whatever is this h_c , so this is equal to r now at this particular value. And now once you cross that value that means, r is now going down and down, and then you are getting a grammatically increased specific cutting energy so that is how we can understand this thing.

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Now, let us see this particular diagram where uncut chip thickness is given at the x . So, this is the chip thickness and here the resisting shear stress is given. So, now how this thing happen, so now, if you consider your chip thickness in 500s of micron so that what we do generally that those type of things are in the tensile testing that we prepare tensile

test specimen and then you do biaxial testing and then you can understand that how it is failure occurs.

So, if you go in the downside that if you reduce your uncut chip thickness of the chip thickness, then next operation comes those things are the turning operation, milling operation where our chip thickness considering about the 50 micron over the 100 micron something like that. So, now, this is the range. So, now, this is the resisting shear stress; that means, how much material will resist when you do when you cut a material with a particular uncut chip thickness or the chip thickness.

So, now, here if you go down and down in the lower side then this is called the precision milling operation that is what we are talking, let us consider it is a micro machining operation wherever uncut chip thickness of the chip thickness is 5 to 10 micron. Now, consider so this is the grain size of the grain of the material, which we want to cut. So, now what is going to happen that if you consider this thing the crystal grain wood grain, so this is more than 10 micron. So, this is the whatever this cross marks are given, so those things are the particular wood grain. So, this is wood grain this is the cavity; that means, some porosity is also there and this is the grain boundary. So, when you are cutting a material at this particular stage at that time what will happen that material actually try to find out a weak point through which it can cut the material.

So, these are the cavity if the crack is the weak point, grain boundary is a weak point and whatever is the void is inside the grain that is also weak, but right now we are talking about the 5 to 10 micron here. So, what is happening here that this 1 micron grain, it will not actually play important role because its depth scale is very, very small compared to the uncut chip thickness. So, what is the primary probability thing that it will pass through the grain boundary. And if some grain is coming in it is where that mean it will cut the grain also at that time this particular whatever void and whatever the defects are available inside the grain that will play important role in propagating the material. So, this is what is showing here in this case.

So, now, once this part is over now if you continue in reduction of this thing, now actually you are going into the detail of the grain now. Now, if you see the dislocation range now, now you have to find out what is the distance between this particular void range here. So, here if you see this thing dislocations are this within the grain, so now,

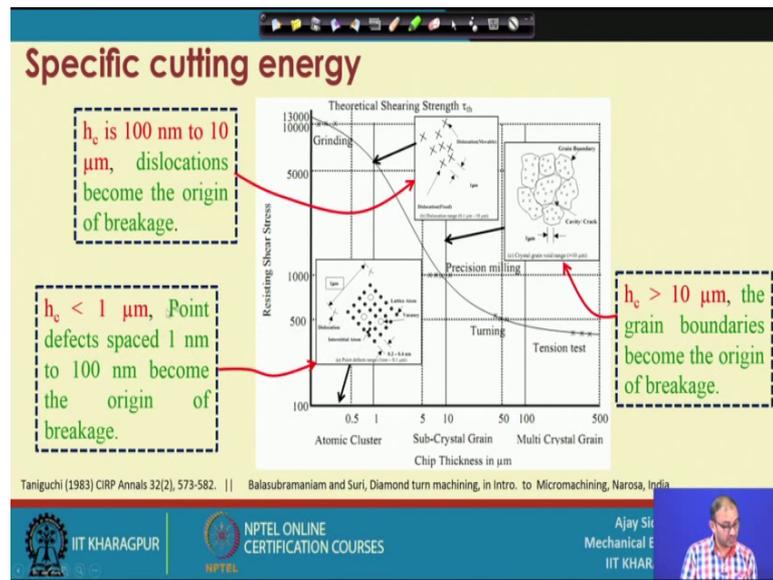
you are talking about 1 micron. So, when you go in this direction, so this is the 1 micron now. So, if you move into this direction here then there is a chance of removing or the cutting of a material through this dislocation correct. So, every time your material will your tool or your cutting mechanism will try to find out what are the weak point of the material in the grain boundary within the grain, and then it will try to propagate through that particular location.

Now, further continue that what depth of cut is less than 0.5 micron. Now, what it will go that it will go within this particular dislocation now this is the dislocation what we are understanding here. So, this is the 1 micron. So, now, we have expanded that 1 micron and then we go inside it. So, now, you can find out that there are different type of vacancy is there, there are interstitial atoms is available, so there are lattice atoms available, and this point defects range is now in terms of 0.2 to 0.4 nanometer. So, now your material removal mechanism or through which a material will remove, it will try to find out this defects within the dislocation.

So, what is important thing about this diagram that is yours uncut chip thickness reduces, the number of defects whatever you encounter at the highest scale it may not present at the lower scale. So, now, you consider this energy is continuously increasing if you reduce the chip thickness. And now finally, you end up with the grinding and this is the theoretical shear strength which is reaching extremely high value here. So, that is what is happening in a precision milling on micromachining that we are we are actually working in this particular area.

Because we are talking about grain and then we are talking about what are the defects within the grain, but we are not going in this particular range less than 5 micron or something because after that many other things made up on your precision in the resolution of your machine to itself will create a lot of problem. And we have on the limitation related to the cutting tool geometry because you cannot scale down a cutting tool beyond a certain limit because after that the material of the cutting tool also play important role what are the grain size, and how you are actually compacting those thing and making it more stable.

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So, now, this is the h_c when you are talking about that more than 10 micron. So, grain boundary becomes the origin of the breakage. So, this is the way it should propagate during the material removal. And when you are talking about h_c is 100 of nanometer to 10 micron then your dislocation becomes origin, because here it was the boundary now it is dislocation and if you go further down then point defect whatever is here vacancy interstitial atoms of those are the point defects. So, those things become the origin of the breakage. So, this one diagram give you overall idea about the how much is the resisting shear stress that means, what we are talking about the specific cutting energy that is also related with this particular diagram. So, it is all almost superimpose over this particular diagram and you will not get any different trend in the specific cutting energy. So, this is what is happening that your number of defects level is reducing if you go down and down into the micro scale.

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Reasons for high specific cutting energy

- Strengthening due to lack of defects
- Strain-rate hardening
- Reduced temperature softening

Depth of cut ↓ → Temp is less → Temp softening is less

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So, what are the different reason we have seen many of them and let us summarise those thing and we have x understood this particular diagram when we started the size effect. So, here we have seen that there are four different location through which we can understand the micromechanics much better compared to the conventional machining processes. So, strengthening due to the lack of defects that we have seen in the previous diagram or previous slide that we are not able to find the in a defects at the small scale of the material of the small volume. And because of that material becomes a ideal material in your way you are not able to penetrate the tool very easily.

Strain-rate hardening, so strain-rate hardening; that means, that at which rate your strain is increasing or decreasing. So, mostly when you are talking most it is mostly connect with the dislocations. So, when inhomogeneities and dislocation those things are there. So, at with respect to time how much it is increasing those things here so that is again one of the reasons for high cut specific cutting energy because it becomes very very harden in that case and material removal is very difficult.

Reduced temperature softening here because if you consider the macro scale machining we know that temperature is very very high in some cases where the depth of cut is very very high and the rpm main feed that is also very high. But in micro machining what we know that we are cutting a very small amount of material, so when you reduce the cutting edge so small material removed at depth of cut is small. Because of that what is

happen a temperature is also less, temperature is less. And then temperature softening is not happening softening is less let us write less.

So, what is happening that when your machine get a micro scale whatever temperature is very very high in this particular zone. So, some of the temperature will go to the tools, some of the temperature will go to the material some of the in the chip and some will propagated hide of the cutting tool. So, whatever temperature is playing important it is softening the material. So, whenever this soft material will come into contact with the tool at that time the material removal will be easy compared to the cold material or the without any increase of the temperature. So, that is not happening in this case because we are not getting a high rise of the temperature in the micromachining right.

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The slide is titled "Reasons for high specific cutting energy" and lists four factors: "Strengthening due to lack of defects", "Strain-rate hardening", "Reduced temperature softening", and "Strain-gradient hardening" (which is circled in red). A diagram on the right shows a cutting process with a chip being removed by a tool. It labels "Chip", "Tool", "Ploughing", and "Sub surface flow Workpiece". It also identifies "Investigation Locations 1: Deformation zones", "Investigation Location 2: Edge radius", "Investigation Location 3: Fracture", and "Investigation Location 4: Chip initiation". A legend lists "Strain / inhomogeneities", "Strain rate", "Temperature", and "Strain gradient". A handwritten diagram shows "Tension" and "Bending" forces. The slide footer includes "Subbiah and Melkote (2006) J. Eng. Mater. Technol 129(2), 321-331", "IIT KHARAGPUR", "NPTEL ONLINE CERTIFICATION COURSES", and "Ajay Sii Mechanical E IIT KHAR".

Strain-gradient hardening because strain is not continuous in this particular case that means, it is not uniform throughout the this particular angle. So, this is the shear plane angle. So, if you consider this particular part here, so this is on shear plane your strain is variable. So, it is very very higher, it is very very low here in this particular case. So, because of that you are getting a hardening of the material hardening here and that is also one of the reason for specific cutting energy. Now, considered this is the example. So, if you are actually pulling a rod, then you will not get a strain gradient. So, strain will be same at every location of the throughout the cross section, but if you bend this thing then

your strain will be very, very high here at the centre, this will be low and again it will be higher this particular location.

So, now bending and this is the tension correct. So, in tension you will not get that much strain-gradient, because it is uniform strength throughout the material, but when you bend it at that time it is a variable. So, that is same thing happens here that one location you are getting a very, very high strain, and another location you are getting a low strain within the same specific zone. So, that is also one of the reasons for high specific cutting energy.

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Reasons for high specific cutting energy

- Strengthening due to lack of defects
- Strain-rate hardening
- Reduced temperature softening
- Strain-gradient hardening
- Plastic flow around a blunt tool edge
- Extension of the shear plane into the workpiece

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Strain / inhomogenities
Strain rate
Temperature
Strain gradient

Chip
Tool
Ploughing
Sub surface flow
Workpiece
Fracture

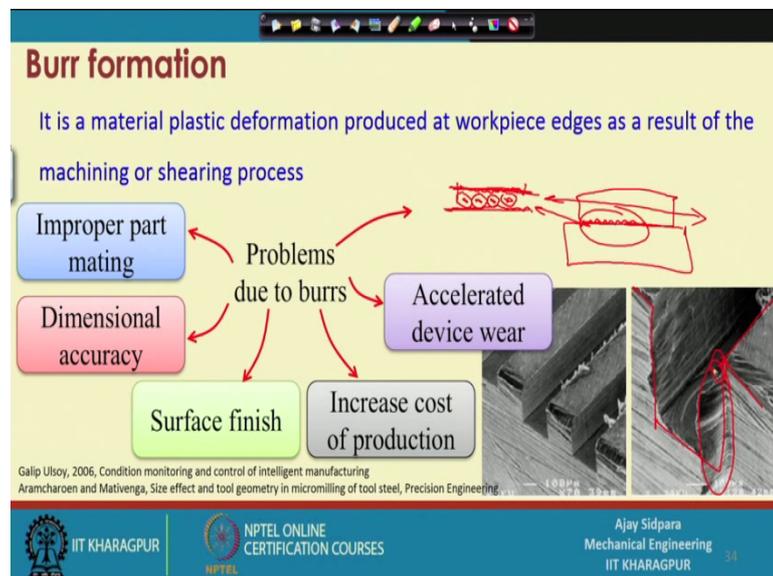
Investigation Location 1: Deformation zones
Investigation Location 2: Edge radius
Investigation Location 3: Edge radius
Investigation Location 4: Chip initiation
Investigation Location 5: Workpiece Deformation UNDER CONTACT RELIEF

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So, plastic flow around the blunt cutting tools, so this diagram also we have seen in previous lecturer or previous slides. So, here what is happening that material is deform head of the tool and some material is actually transferring to the sites, and some of the material accumulated on the face of the cutting red face of the cutting tool. And because of that what is happening that this plastic flow actually creates a lot of amount of forces when you cut the material. So, we know that if force is increases and your uncut chip thickness is continuously decreases then your specific cutting energy increasing depending on that earlier equation. So, we consider our tool is a blunt because we know that at micro level there is always one cutting edge radius which is playing important role in the cutting operation.

And extension of the shear plane into the workpiece. So, now, if you consider this particular thing that this particular shear plane, so this shear plane actually may get extended inside it. And because of that reason that now you have to pull out large amount of material when your shear plane angle increases, so that much amount of energy you have to spend again the force requirement will be very very high and that is also one of the reasons for high specific cutting energy. So, these are few reason there may be many depending on the materials and defects of the material, if it is a in anisotropic material, if it is a homogeneous material every time you will get a different reasons for increase of the specific cutting energy.

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Now, coming to one new topic that is called burr formation, because we know that when you do cutting of any material, you end up with some of the materials, which still stick to the surface and the later stage you have to do something to remove those materials. So, these are the unwanted material. So, whatever we are talking about this thing is these part. This is the part, this is the part because now if you see this is the channel which is created, but some material is still stick to the surface.

So, now what is that burr. So, it is a material plastic deformation produced at workpiece edge you mostly find at the workpiece edge only. So, these are the top edge, so this is called top burr; this is the edge at the entrance of the exits, so at that time you can call is entrance burr of the exit burr as a result of the machining or the shearing process. So,

these are something which we have to ever do we have to minimise, mostly avoid is very difficult because then you have to set a process parameter in such a way that you can reduce the burr formation. So, what are the problems due to burr formation. So, there are improper part mating. Now, if you consider this particular part and you want to make this part with the another part with a flat surface, then this particular burr it will not allow to make this both the part together and that is the reason that you are end up with the improper mating of the parts.

Then dimensional accuracy because now we know that we have to measure our dimension from this particular edge correct. So, this is the actual shape of the thing but because of the presence of this thing, it is also difficult to measure at micro scale that from which location we have to start the measurement of this particular shape. Suppose, you want to measure the length of this particular channel then starting point is very confusing here unless you remove this burr very properly, so dimensional accuracy also creating problem.

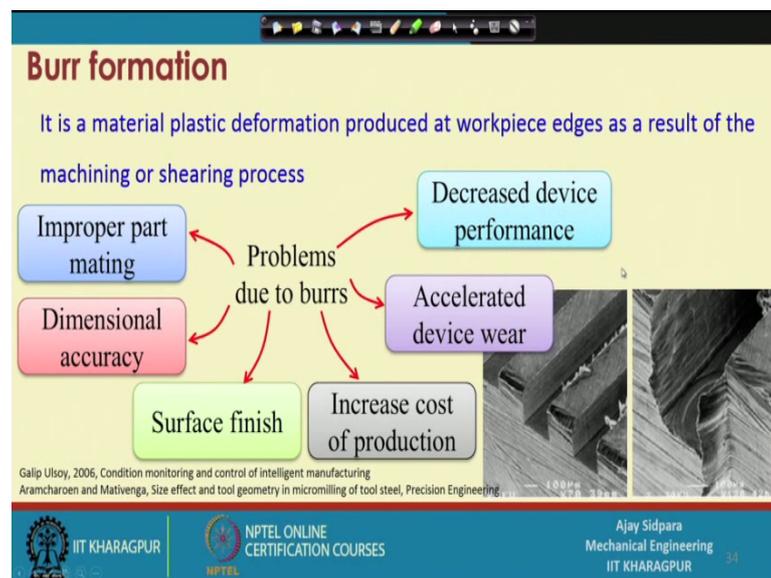
Then surface finish because right now what we are looking at it from the top surface only, but burrs also create some problem at the surface which we have some functional requirement. So, surface means decreases with the presence of burr. In case the cost of the production, because once this burr surface end then what you to do you have to apply one deburring operation that deburring operations are actually non-productive that it does not at any value to the component, it is just to remove this burr. So, it increase the production cost because ultimately your object is to remove all the burrs from the components. So, increase a production cost is obvious.

An accelerated wear off the device is now you consider the burrs are present here and this particular surface as a one relative motion. Now, consider that suppose you have one workpiece. This is the workpiece and some burrs are located on the top surface. And there is another component which you have a relative motion. So, this is moving in that reciprocating in this. So, whatever these burr surface and what it will do that actually it this burrs will be broken and that will become the interface between the two surfaces.

So, let us magnify this surface when you will find this is the top surface and this is the bottom surface and what a burrs are removed, so this will be in between these two surfaces. And this particular burr will actually increase the further wear of this particle.

So, now, these are the thorough an element now it is note at the any of this surfaces. So, now, these burrs are actually again accelerate this particular wear that means, these particular things will be again dimensionally incorrect and this will also same thing happen in this case. So, it will further increase the wear of the abrasive any component because now this burrs considered abrasive particle, because there are sharp also some times and that will actually remove material from the components, and that is why decrease the device perform.

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Because when you consider bearing operation and if you find that there are small amount of debris in between the bearing and the races at that time this will actually give a non uniform rotation or the non continuous motion that will reason in the decrease of the device, you have to replace the bearing. So, this is the starting point of the burr formation.

We will continue this topic in the next lecture, and let us understand this burr formation in much better way in the micromachining operation.

Thank you very much.