**Technology of Surface Coating**
**Professor A K Chattopadhyay**
**Department of Mechanical Engineering**
**Indian Institute of Technology, Kharagpur**
**Module 11**
**Lecture 40**
**Performance Evaluation of HFCVD Diamond Coated Tool**

Performance Evaluation of Hot Filament CVD Diamond Coated Tool, now this diamond coated tool has created lot of interest among both academician and industry because of the simple reason that this is a substitute for this classical single crystal diamond or PCD diamond. Now single crystal diamond and PCD diamond has many limitations and restrictions in their use, as for example single crystal diamond is very brittle and it has very limited use in all precision machining of aluminium and copper.

But this cannot be used for heavy duty task of machining say for example a composite consisting of both metal and ceramic or silicon like thing, or it cannot be even used for machining some of those areas where the machining conditions are not so continuous, so uniform. So in that case because of the fluctuation of the force, the tool may suffer premature brittle fracture.

Now when PCD came into being, this weakness of diamond could have been minimized or even eliminated in most of the cases, however one of the shortcoming of this PCD is that its geometrical restriction, so this polycrystalline diamond compact could be only manufactured with some very well defined simple geometry.

So this tools can be used for say normal turning facing operation but when it is going to be a complicated milling task then we do not have any suitable tool as a diamond tool, though we know that diamond is the only solution to this machining problem. Say for example when it is machining of aluminium silicon alloy with varying percentage of silicon.

Then if we use a carbide tool, this single carbide, then this presence of silicon causes a high rate of wear and the tool fails immediately and with percentage of increase of silicon, the tool becomes almost unsuitable for such machining task and in that case PCD can be a good candidate but when it is pocket milling or slotting with some milling cutter, with some complicated geometry as it is used in automobile industry, then one can find out the limitations of this PCD.

Now when we have this CVD product, this is hot filament special CVD process, when we have such a CVD product definitely that is an remarkable achievement from this coating technology field and this particular expertise and that has solved the problem because the whole idea in the coating technology is that on a substrate, which is preform, we can put a top layer which will fit to the geometry which will follow the geometry of the substrate but only enhancing its capability and property.

So following that principle we had TiC, TiN, aluminium oxide, titanium carbonite trident, many more. But, this super hard materials in the form of coating that was a long desire and a demand which could have been fulfilled at last and we have here diamond coated tool which can be used for such machining task.

Now the question is for any coated tool, we have all sort of test or examination for screening, that means after the coating is done we have physical characterization, we have also mechanical characterization and in mechanical characterization mostly what are those examine, hardness, micro hardness of the coating then adhesion of the coating with the substrate and also the frictional aspect and these are all some classical way of doing the thing and standardize and these are simulation but it is just for ranking the coating but it is not exactly a data for prediction of the performance of that coating in actual field.

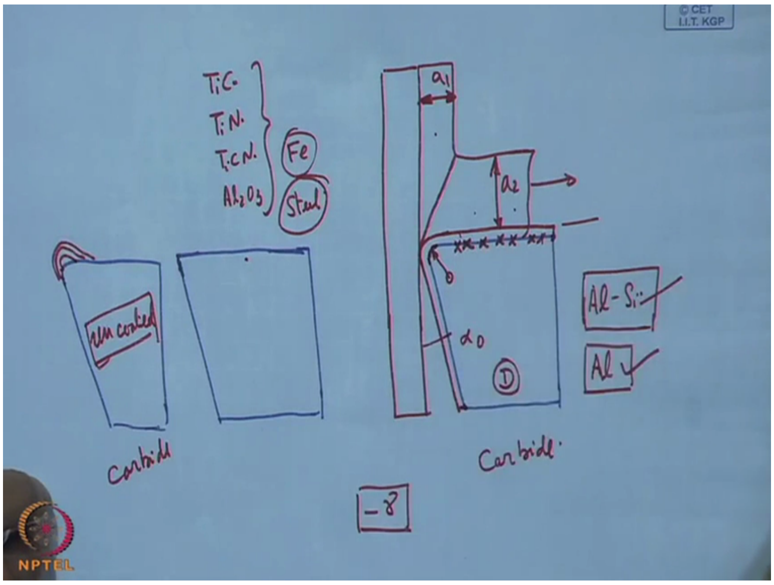
So there always been a requirement necessity of doing the actual test in the field and for that we need to do this machining test even with diamond, CVD diamond coating. Now what we see here, now HFCVD Diamond Coating on Carbide Cutting Tool, now this carbide has to be there as the substrate and we know that the difficulty in holding diamond over this carbide it is just not a substrate and there are lot of pre-treatments treating the substrate, passivating the cobalt or roughening the carbide grains, interlayering, putting some metal layer, matching the property with that of diamond, there are certain coating with metal which are good carbide format and so on.

So lot of efforts have to be put to get a proper chemistry of the substrate so that ultimately it becomes a good receptor of this diamond coating. Now even after that, the main problem remains with diamond is that how to have the best possible adhesion, how to have a smooth coating and how to put this coating with the available technology on a complex geometry of a tool, particularly the rotary tool, those which are all sort of end milling cutter used in mostly in automobile industry.

So carbide has to be the best candidate because on steel, the main problem will be that basic presence of iron which like cobalt can be also counterproductive in holding diamond rather it is a risk of getting diamond converted to graphite at the interface because of the very presence of iron, though some layering can be done, however at that temperature of deposition, this diamond co-efficient of friction sorry, co-efficient of thermal expansion and that of steel, that mismatch can lead to also cracking.

So all this thing can be considered and finally it comes to that, carbide is the best available substrate considering this restriction imposed by steel and also few of those ceramic like silicon nitrite which can be also good candidate, so far as its thermal co-efficient is concerned and there is no cobalt, but toughness wise, carbide is always a better candidate. So finally it is the carbide substrate on which this diamond is deposited.

(Refer Slide Time: 09:42)




Now here one has to see how this cutting action of diamond coated tool that takes place and also the tool geometry. So let us see quickly this cutting action, now here what we see this tool, we can have an uncoated tool but normally with carbide what we do, we do not have a sharp point but we have to put a radius. So similarly here if we have to put a radius, it will look like this and over that we have to put this diamond coating.

So that is the diamond coating, here one thing is very important that this is called the edge rounding radius. Now this edge rounding radius has to be properly chosen, this is important for reinforcing this edge and also for good retention of the coating and then what we see here, this is the workpiece and this workpiece have certain uncut layer and then we can also see this is coming like a chip, so this is uncut layer thickness, this is the thickness of the chip, when it is coming out in this direction and that is the separation between the material before deformation and this is after deformation.

And this is clearance angle and here ofcourse we have put this rake angle as zero but for the carbide what is quite interesting when it is still cutting rake, it is, we take it as negative rake, negative rake angle but when this, this diamond coating, it is particularly tailored for machining aluminium silicon alloy or even aluminium alloy or alloy without having any silicon, just rolled aluminium.

Now in aluminium machining, the main problem is that it does not cause any wear on the tool, so it is not a very hard material or it is not a material which can cause some diffusion but this is a material which can cause sticking, heavy sticking on that tip of the tool. So on uncoated carbide tool, what we can see heavy built up of the material, so on this surface, if we use this thing, this tungsten carbide tool.

And for machining aluminium alloy or aluminum silicon alloy, we can find out heavy material built up. So that becomes the greatest challenge in machining aluminium and it is not just the wear on the tool and this material gets re-deposited on this work surface not in case of diamond but on this surface, and as a result it leads to poor surface finish of the machine surface.

So for diamond what is expected because of the inertness of diamond against aluminium, this is going to be one of the best candidate for machining aluminium, at the same time it has a twofold action, this silicon can cause wear on this carbide, this is very very abrasive in nature and aluminium is sticking in nature. So in a material you have two kind of elements, components, one causes abrasive wear and another causes sticking.

So this is only diamond which can solve this twin problem, sticking problem and resistance to abrasion, so that is why it is so in demand that this tool and with this coating we have unlimited opportunities of using this diamond coating on varieties of cutting tool using this coating and for machining those materials which has a tendency otherwise or all material, say for example this aluminium can also stick to titanium carbide or titanium nitrite or carbo-nitrite.

So what we can say from this that, this classical coating which are all this family, this TiC, TiN, TiCN then Al 2 O 3 which are well established, these are well established CVD coating for machining iron group that means steel. These are well established and highly performing but these shows their poor performance in having this aluminium machining.

So this is not just the tailored coating though they are quite successful in other areas so it is mostly diamond coating though diamond is not a good candidate at all for iron. So whatever may be the case ultimately it is diamond, so putting the diamond on this surface that is one task and also then to see how good it is, two issues are there we can see that this cutting action so what we can see comparing, in comparison to an uncoated tool which is an uncoated tool.

Here what we see that immediately force will rise and surface finish will be poor but in this case it will live a cleaner cut provided this is very important, provided this coating it has proper characteristics of diamond, number one, so and number two this is more important that adhesion at this interface, because it is also our experience to have good adhesion of TiC, TiN or TiCN.

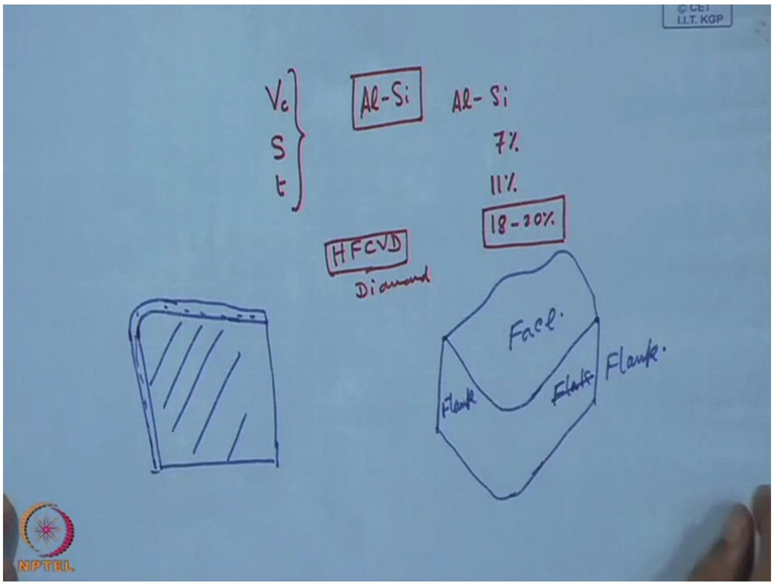
This carbide we should not any problem when we put TiC over this and then we have the top layer TiN or aluminium oxide. So those things are well established for this class of coating, no problem at all. But when it is diamond coating then this becomes a serious issue of having this particular adhesion strength issue at the interface and along with that what is very important here also to have a very smooth coating.

Smooth coating means actually if we see the morphology of diamond coating which is done by CVD and that of the coating of TiC, TiN or TiCN or even aluminium oxide, by CVD we can see this roughness is more in case of diamond. So if you measure the roughness, we can find that is a rougher surface. So that means here we have relatively large crystal which are well defined which can be recognized under the microscope and sometimes unfortunately there can be some outgrowth in few of the zone.

And those points of outgrowth naturally those, in those areas we have highly rough surface and there will be mechanical clogging between the cheap material, this cheap it is aluminium silicon, so one thing has to be made clear here that aluminium is chemically inert towards diamond so that part is well understood.

However this surface is not smooth so we have like mountain peaks and valleys and we have some cavity like thing, so the whole material almost like a (())(19:22) gates entrapped and that those, in those areas unfortunately some aluminium stress can be also detected. So that becomes the places which can also raise the force, so there are two objective, two immediate objective and one is how to improve the situation adhesion so far as adhesion is concerned and number two is how to get a smooth coating and these are the two things which need to be tested in the actual machining test.

(Refer Slide Time: 20:18)

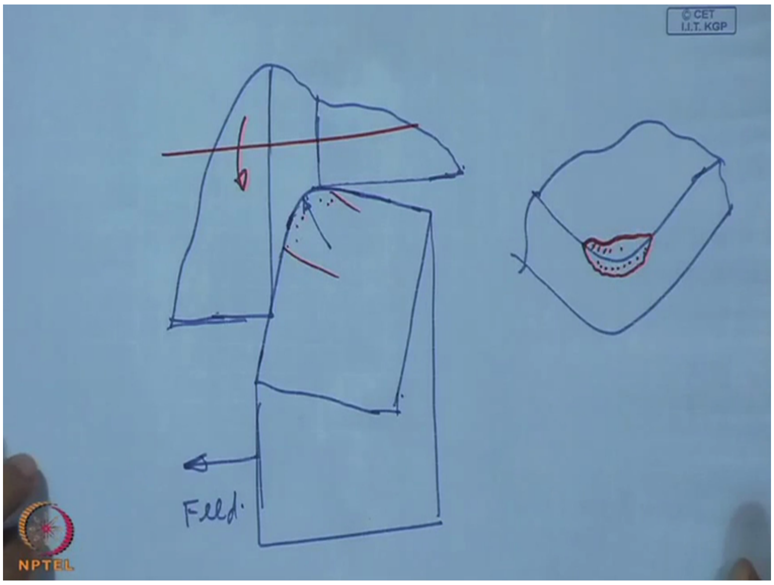



So this is actually Machining Test, so here what we have to consider the cutting velocity, feed and depth of cut. So in case of aluminium and silicon which is the place where diamond is, diamond coating is in great demand so by choosing this we can also have aluminium silicon which can be say for example, it is called hypoeutectoid that means 7 percent or it is actually utectique that means around 11 percent or hypereutectic which can be around 18 to 20 percent, very very abrasive.

One of the greatest challenge in machining of this one, aluminium with 18 to 20 percent and this becomes a challenging task for this HFCVD diamond coating because here the abrasive action and non-uniform action, non-uniform silicon that gives always an intermittent impact over this diamond coating leading to its fracture and breakage. So this is also, so here the coating adhesion improvement is one of the greatest task, so that has to be looked in.

So in this machining test, cutting tool and for aluminium machining what we take a tool with a positive rake angle that means sloping downwards and here also what we see that this radius. So this is the coating. Now if we like to see the tool we can also have a look like this, part of the tool, so this is the face and that is the flank, this is also flank, so this tool actually looks, this is the cross-section and here we have the diamond coating and if we engage this tool, this we can also have another illustration.

(Refer slide time: 23:22)

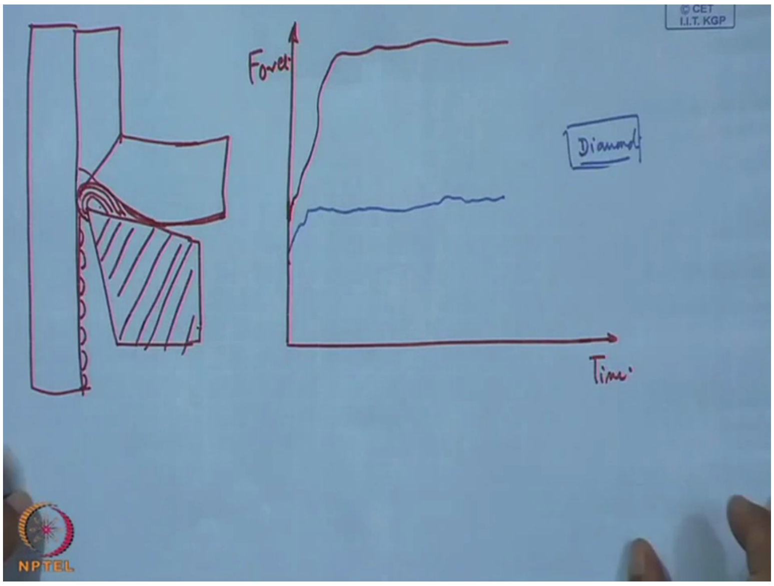



Let us have a quick look, this tool it will be a tool like this which is engaged in machining. So this is an insert and here what we can say, so this is actually part of the tool which is moving in this direction with the feed. So this is actually the nose, nose portion, nose radius, so this is actually the nose radius. What we have shown here, nose radius. Now we have coating over covering the face and the flank so this side is called the principle cutting edge that means here this side is the principle lank and this side is the auxiliary cutting edge, that means this side is the auxiliary flank.

Now when it is in engaged, now the delicate part would be that there is every chance in case of a poor coating. What is going to happen, poorly adhering coating, we can have removal of the coating just like this. So that means from this surface, we have removal of the coating. So this is substrate exposed and this also substrate is exposed.

So this is, so here we have the coating but this is (())(25:25) severely stressed and because of that the coating is removed it just at the moment it is brought in contact with this work piece. So this is actually the spinning access, a part of the job we have shown here so it is done in a lathe. So this is going to be a major problem if we have very poor adhesion at this point and this can be the reason of either a poor adhesion or the surface is too rough, so when this chip flows there the drag force is quite high so as a result of this there can be a flicking.

(Refer slide time: 26:18)




However if we have a good coating, that means a Comparison with an Uncoated Tool, so let us see how we can see that part. So when we have a uncoated tool in that case what we see, material built up, material will pile up over this surface, that means this is the cross-section, so material will piled up and this material will be partly transferred to the work piece which is here and a part will go with the under surface of the chip, with the under surface of the chip also it goes.

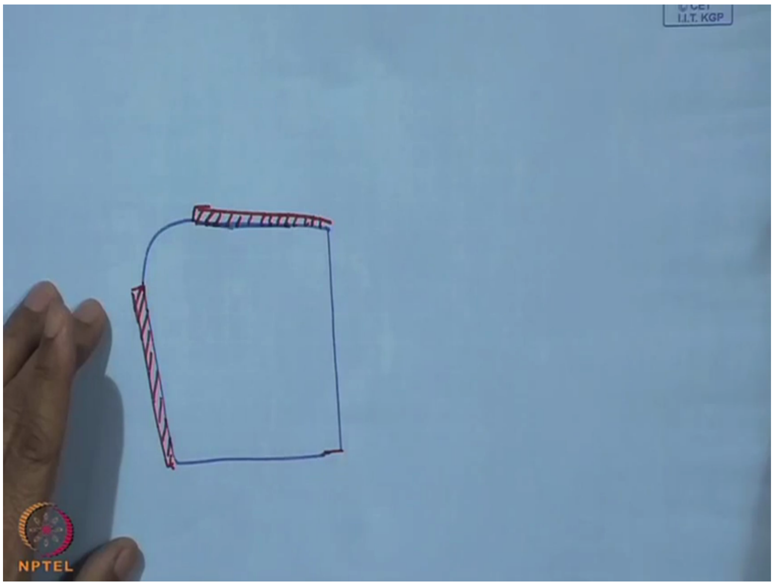
So this is the situation at this point, so this type of material built up is really harmful. It actually reduces the capability of the tool because of so many reason. Number one we see that the inter-cutting geometry that is totally distorted and that is because of the coverage with this built up material. So this geometry, sharp geometry is not exposed and it is covered by this built up material.

Number two, because it is now aluminium against aluminium, so your force will be quite high and then the geometry is unfavorable and then what happens, part of this which is little bit projected outside that will be broken later on and that will be re-deposited on this surface and as a result what we see if we plot it here, this is the force and time.

So with that what we can see that force at the very beginning it starts with a very low value, however it starts with low value but it goes to very high value and it goes like that with time. So this is actually the spectrum of force because of this situation. But when we have a diamond coating, what it means that from the very beginning we have a low value, low value something like this and this difference is because of the simple reason, the diamond is inert to aluminium oxide and what we get in this case, a absolutely clean cut in contrast to the built up edge formation with uncoated tool.

So this built up edge formation with uncoated tool it is just explained here and this built up edge is totally absent in case of diamond tool, it is a clean cut and not even a single stress of aluminium is written. However what we find if the surface is rough in that case, because of this inter-locking what is going to happen that during the course of time at certain point the coating may rupture and because of this rupture that substrate will be uncovered, what we have shown here, this substrate will be uncovered and in that area again we can have material built up.

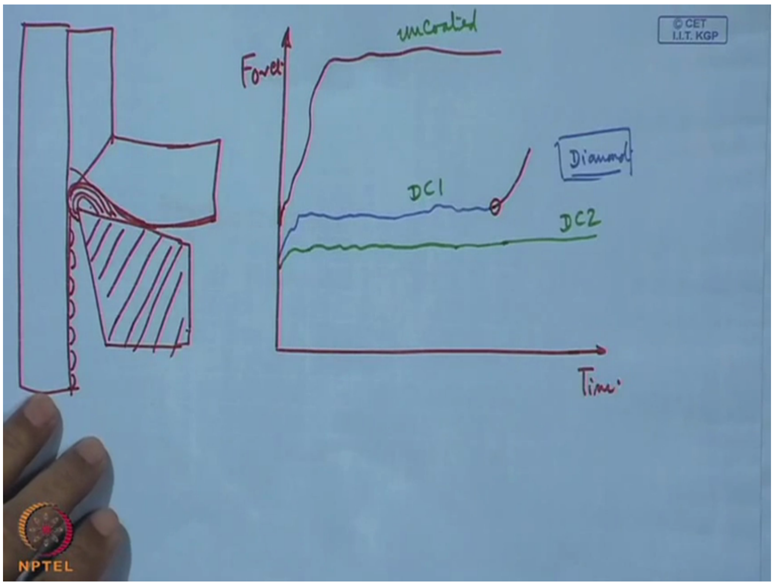
(Refer Slide Time: 30:48)



That means what we can illustrate here, maybe we can illustrate this point just by another diagram say originally this is the surface, and we have coating all throw but now what happens the coating is ruptured something like that, so this is the rupture of this coating so this part what we have shown in this diagram here in this area, so coating is ruptured but other places coating is intact but that is not the issue here. It is actually the zone where the tool is in contact with the work piece and that is the area of interest to us and there is tremendous amount of stress associated with heavy high degree of deformation.

And because of that it could have been that this adhesion strength was not adequate in comparison to the stress which was developed and as a result this coating got separated and now this is behaving like one uncoated tool.

(Refer Slide Time: 32:28)




So in that case what may happen, that a tool after this point it can also go like this, it can go like this, so from this force spectrum, if one follows the force spectrum which will be continuously monitored by the dynamometer.

One can see that when there is a rise of force immediately he can also look into the, after stopping the machine, he can also have a look into the cutting edge, microscopic observation he can also make and to confirm that whether the coating is removed or not, in most of the cases it is our experience that this rise of force is always associated with rupture of the coating and as a consequence of that you have always a material build up over this surface like that material will build up and this material will be transferred over the surface and then this will also cause rise of force.

So this has to be improved that means all the process variable at the upstream side that means where we have the deposition process, actual deposition process. So there, from this information, corrective steps have to be taken whether it is the preparation of the substrate, whether it is passivation of the cobalt or enhancement of the surface roughness to have proper holding or the pocket for retaining the diamond seeds.

So these are the issues of immediate attention and one has to address plus the parametric combination of all the process variables like CH4 2H2 ratio, this is number one, then the process pressure within the CVD chamber then the stand of distance and the substrate temperature. So all these are some kind of influence on the overall adhesion at this interface.

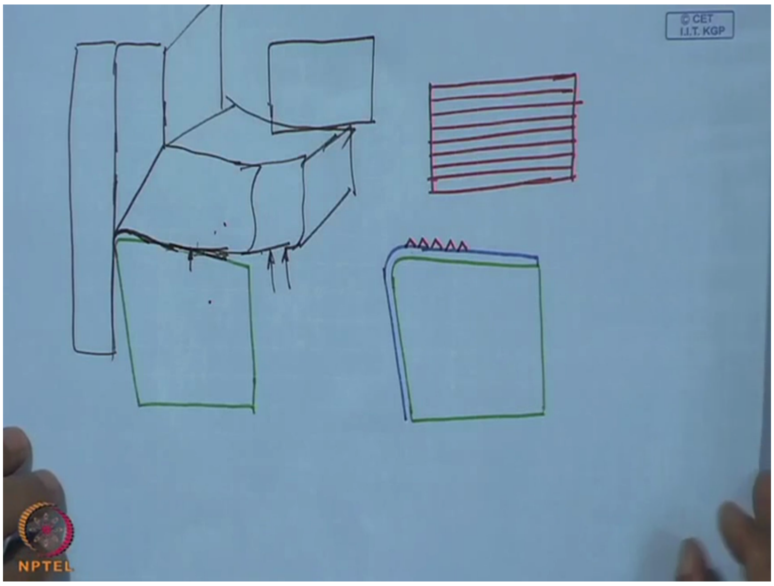
So by proper attention one can also have a look on this that we can have another coating on this curve, we can show that we can have another coating which can be also shown here its force spectrum and it is still lower and it can go still farther without any problem and in this case we can say, say this is diamond coated tool 1 and this is diamond coated tool 2 and this is one uncoated tool so from this force spectrum.

One can come to the conclusion that heavy material build up has taken place in this uncoated tool and this is one coating which has a very good start but later on because of this continuous rubbing with a high force ultimately there could have been a crack developed at the interface and which could have propagated leading to the partial rupture of the coating and finally in that exposed area aluminium got stuck and that gave rise to this force.

And at the same time this aluminium when it gets re-deposited here then surface roughness also can go up but if we have a coating with a better adhesion and better smoothness then not only adhesion, because of the good adhesion better adhesion, life of the coating will be more, but at the same time because of the less drag force or the sliding force, chances of removal of, partial removal of coating that will be also remote in that case.

So this way one can look into this issue of coating adhesion and also the smoothness of the coating which is also very very important in that for the retention of the coating. Now one thing also we can look, this uncoated tool and the diamond coated tool, if we compare the chip which they are producing particularly the underside of the chip, this will be a good comparison showing that inertness of the coating with diamond and a tendency of adhesion of the chip with the uncoated tool.

(Refer slide time: 38:15)



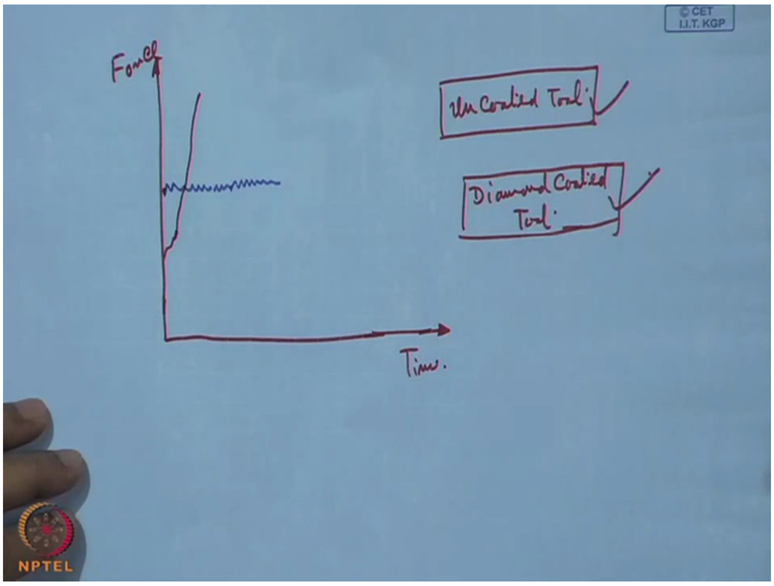
Say in this case with the uncoated tool we have this tool and on this with a coating, this is the coating. So what we see in this case already there is some material adhered and the chip is flowing over this. So this chip with this aluminium against aluminium and it has also inertness, so there we have a well-established stagnant layer. So when we see the underside of this chip, it is actually underside, we have aluminium which is heavily deformed that means underside of the chip if we examine when it goes like this, this side when we observe this underside of the chip.

This is having certain width, so when we see this underside of the chip, it is a heavily deformed layer but when we observe this thing of the chip which is sliding over this diamond surface, it is interestingly we can see some rubbing mark and it is a almost like a clear cut that means the chip is moving in this direction and if we see the underside we can see just some rubbing (())(40:19) very regular it depends upon the morphology of this coating actually what is going to happen, here we have diamond which are also having some, looks like some crystal but finer in size, very fine small in size but still these are the sharp points.

So when this aluminium is sliding past that, it is almost working like an abrasive tool just like one diamond abrasive tool and since this grips this sharp points on this coating that is the top layer of this coating that is surface of the coating with all those crystals and since they do not have any kind of adhesion, so they give a very clean cut and we can get sharp point over this surface.

So this also gives a clear idea that diamond is inert towards aluminium and this carbide that is also having some kind of affinity, so it cannot be a good candidate. The most important thing here is to find out how to smoothen the surface so that we can have still finer scratch and it is wider but we can have high line density that means we can have density of line should be still higher and that will be reflection that the coating is rather smooth but here we find that coating is not so smooth and we have wider gap between this scratch line.

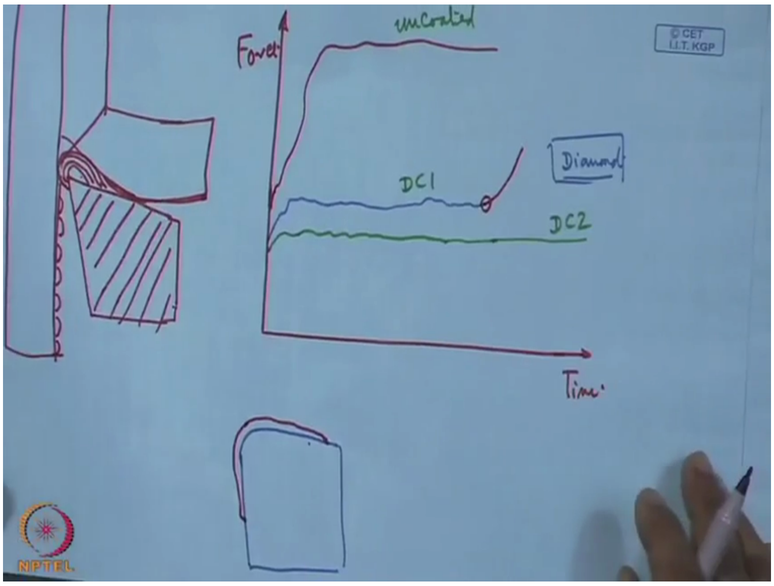
(Refer Slide Time: 42:32)




So this is Cutting Force that we have already mentioned and in this cutting force what we can also see, sometimes what also happens that originally the uncoated tool, the uncoated tool that is smoother than the diamond coated tool so there is no doubt about that. So diamond coated tool, if we consider diamond coated tool compare the roughness with that of the uncoated tool, this is smoother and that is rougher.

So one would expect and it is not unnatural and it is quite lightly that at the very beginning the uncoated tool comes with a low value of the force so it can start with a low value of the force from this point and then it rise to that value quite high but a diamond coated tool, tough it is rough, so its starting value will be quite high, but it does not change because though it is rough but it is rough at this point but it is inert so there is no change in the surface of the surface characteristic.

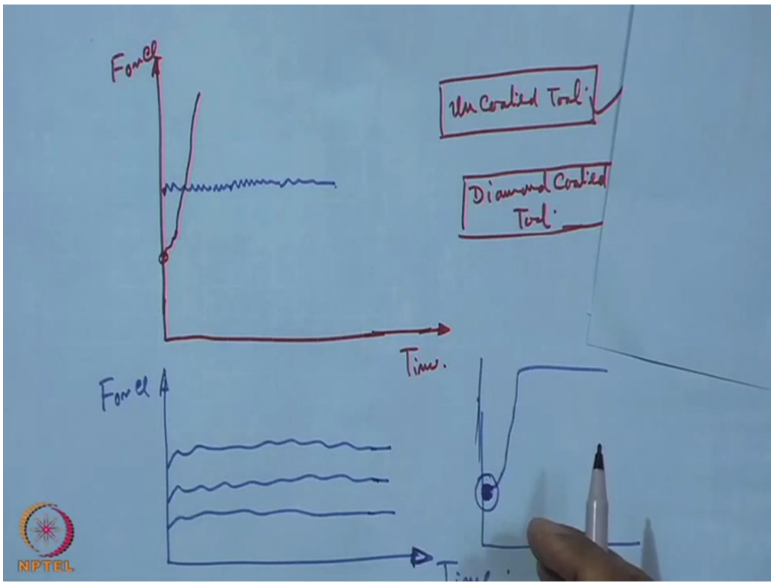
(Refer Slide Time: 44:14)




What we have shown here that there is no change in surface characteristics or friction characteristics. So when we have such situation continuously there will be a rise of force and when this build up edge becomes almost a steady, then we have a steady high value of the force. High value of the force here and this can also since it is a soft material this can also plastically deform and it can go like this. So finally what we see here it is just not a built up edge rather we should call it a built up layer extending, it is almost like that, it is almost like a built up here, very stable.

It will be extremely difficult to separate it mechanically it has to be removed chemically, so it covers the entire rake then this edge and a part of the flank. So the material flows down the flank so the entire area is covered with a deform layer of aluminium. So with that we have a steady force with a very high value.

(Refer Slide Time: 45:37)




Now what we can see here that this is a higher value, no doubt, compared to this point. This is also a steady one and it does not change with time only the case what we have mentioned if there is a premature removal of the coating in that case it can go higher up. But what is interesting here, that we are always to be careful to look that whether this coating fails at the very beginning.

So we can also again refer to this diagram, so this diagram is so relevant in this particular context that with such a situation what we can see that if it happens just at the moment the cutting tool is engaged in that case we cannot even have such thing, now normally we have a steady low force and that depends upon the roughness of the coating.

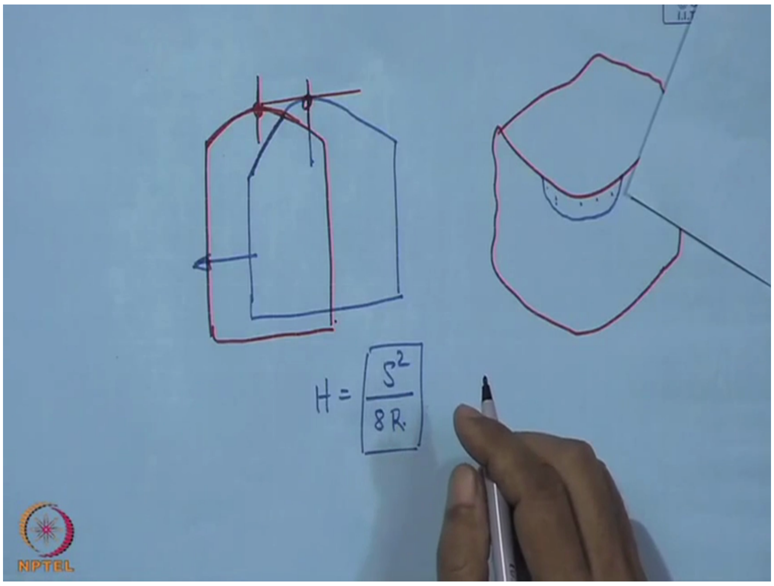
So that means if we have a force here and if it is a question of time then we can have different level of force with the same diamond coating but having different roughness, this can happen. It is only the contribution of the surface roughness. So it is very smooth coating, this is an intermediate and here surface roughness is quite high.

However in this cases adhesion is good with the substrate and all are working quite satisfactory, but if the coating fails then what will happen, immediately, so it may be just a low value followed by like this it can go up, so this low value means it is because of the diamond so your starting up value was quite low but because of the breakage of the coating it goes quite high.

So from the force spectrum, we can also see that this diamond coating which has a start but which is short lived and as a result of extremely poor adhesion, it could not even take the immediate load of cutting just at the moment it is engaged and a portion of the coating is just gets removed and the substrate is exposed and this is situation where we can also have such thing.

Surface Finish of the Workpiece, surface finish of the workpiece is one of the criteria because diamond is an inert material for aluminium and in that case even under dry condition we are expected to get a very good finish, however this depends not only on the inertness of the material but also on the roughness of the coated surface.

(Refer slide time: 49:44)

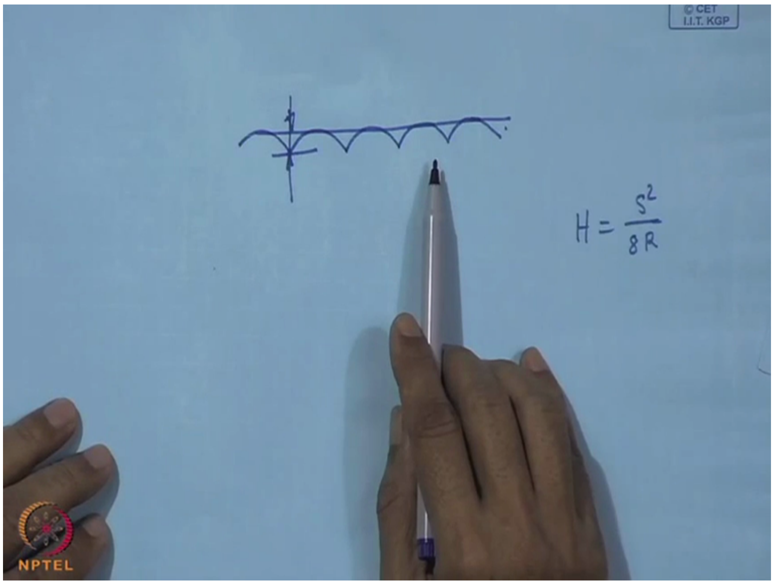



Now surface finish will be influenced strongly by this part of the coating, let us have look, if we just see this thing, this is the tool which is moving in this direction so after 1 revolution of the job this will be another position so this tip, this roughness of this area, that means if we draw this isometric view of the tool then the roughness in this zone, that will determine the roughness micro irregularities on this surface.

So what is going to happen that theoretically the surface roughness will be given by S square by 8 R, where R is the nose radius of the tool and this nose radius we have already mentioned in this diagram, this is actually the nose radius, so this nose radius what we have shown, so this is the feed and that is the nose radius. So that is the theoretical value.

Now on that we have to superimpose a very other thing but since in this case the material is inert so it is expected to give us a very good value of surface finish but since we have some roughness on this surface that will have some kind of influence and depending upon the smoothness of this grain, that means the size of the crystal on this coating and their distribution whether we have some outgrowth on this surface that will finally decide what will be the final value on the surface roughness.

(Refer slide time: 52:30)




However what we see if it is a rounded nose in that case we expect theoretically a surface roughness like this. So this will be the height of the surface roughness, now when it is the diamond coated tool, we approach very close to this but with the uncoated tool, where we have just what we have shown because of this, this picture will be very relevant because of this material built up, we have all sort of material that will be deposited and that will reduce the finish or that will increase the surface roughness.

So then it will not follow that formula, it will be greatly deviated far away from this relationship A square by 8 R, so when it is the machining with diamond coating, we can still have very clear feed mark and during the course of machining if we see that those feed mark are missing then from that point we can apprehend that for some reason this coating gets removed from the cutting edge and that leads to a poor surface finish.

So this way either during the process we can measure the force, we can also measure the surface roughness of the diamond coated tool, we can also see this roughness value, another very interesting thing since it is a very inert material towards aluminium, it say reflecting surface, it is shining surface but when it is a carbide coated, when it is an uncoated carbide we get a matt finish.

So when it is a diamond coated tool and so far so long the diamond remains in that, as in the form of coating on the tool, we get really a glossy surface, reflecting surface and the moment the diamond is torn or gets detached in that form what we have shown here in this form, so on the workpiece immediately we can see that this is the area so here we should get a reflecting surface, but the moment some coating gets removed, say from that point we can also have a matt finish. So from this physical observation also it is possible to speculate about the condition on the diamond coating.

So with that we can make a small summary of today's discussion that this diamond coating by CVD has enormous potential in the area of machining of aluminium silicon alloy and many similar materials particularly which are needed to be machine by milling operation which requires all sort of small rotary tools and where this PCD type tools has certain limitation in their use.

However this diamond coated tool to be tested and to be machined before putting in to actual use though we conduct routine characterization steps for example measurement of hardness, friction then adhesion or physical characterization considering the purity of the diamond or morphology of the diamond but still field test is essential and for this field test a machining test procedure has to be followed where we can systematically study the chip, type of chip because when it is an uncoated chip and a chip coming out of a diamond tool, they are quite different in their shape and also in their deformation pattern.

Then the force spectrum is a good indicator of whether the diamond is existing on the tool or it is removed so immediately force spectrum changes and that is a good indicator on the survival of the diamond coating. Similarly the surface finish or surface roughness that can be also looked into because when it is diamond we always get an inert surface because there has not been a trace of aluminium which gets deposited on the diamond because of its remarkable inertness.

But once diamond gets detached in that case, immediately the surface roughness pattern changes. One thing is also important that adhesion part is extremely important but also the roughness of the coating, roughness of the coating means roughness of the coating influences the surface roughness as well as the cutting force.

So if we have a smooth diamond coating then definitely workpiece surface roughness can be further improved, not only that, force level can be also reduced and the risk of detachment of diamond is also further reduced.