Machining Science - Part I Prof. Sounak Kumar Choudhury Department of Mechanical Engineering Indian Institute of Technology Kanpur

Lecture – 02

Hello and welcome to the second session of discussion on Machining Science. Let me remind you, in the first session, we defined machining as one of the manufacturing processes in which the desired shape, size, finish and accuracy is obtained by removing the excess material from the workpiece in terms of small chips. Different surfaces we get because of the relative movement between the tool and the workpiece.

We have seen the different kind of relative movements because of which we can get a flat surface, we can get a cylindrical surface, either it is an external or it is an internal or say tapered surface and so on. Then, we said that the basic mechanism which is responsible for material removal is the plastic deformation and before the metal gets segregated so that we can get the desired shape size etcetera; the material has to go through the elastic deformation, plastic deformation, then the strain hardening and then it gets fractured.

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So, we said that this is the elastic limit; this is the tensile test of a mild steel bar and here the material gets fractured, this is shown in an example of a mild steel material. For brittle material it is not like that; because brittle material does not go beyond this point it breaks because the material is brittle and it cannot withstand the high strain rate. So, we get the discontinuous chips.

Now, for the mild steel or for any ductile material what we will get is the elastic limit and, then it becomes plastic followed by the strain-hardening and then it gets fractured. As the chip is segregated from the workpiece, we get different kind of surfaces.

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Then, what we said is that this is the region where the material gets strain-hardened.

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Tensile Test – Mild steel bar	
 Most metals and alloys do not show this type of pronounced initial yielding and change from ELASTIC to ELASTIC-PLASTIC deformation is gradual Region DE Strain hardening 	(Vield) E (Fracture)
 Following the transition from elastic to plastic behaviour, the load required for further deformation increases 	1 × ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
 The material being able to withstand the increased load despite the uniform reduction in cross sectional area is called strain- 	0
hardening or work-hardening	Extension
 Two opposing factors operate to determine the load required for a given extension Strain-hardening leads to an increase of load Reduction in cross-sectional area leads to a decrease of load 	
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The strain hardening is actually defined by the material being able to withstand the increased load despite the uniform reduction in cross sectional area this is called the strain-hardening or sometimes it is also called the work-hardening.

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After that we said that the necking occurs somewhere here because the extension becomes large, the strain hardening is unable to cope with the decrease in the cross-sectional area. So, when the necking is formed, the deformation happens locally and then it gets unstable and gets fractured at any time between the E and the F. This we have discussed in the first session.

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Now, let us discuss the stress and strain in brief because we understand that material removal is basically because of the plastic deformation and high strain rate of deformation. The mode of deformation of a material under applied load will depend not only on the magnitude of forces and the mechanical properties of the material, but also in the way in which the forces are applied and their combined. Nominal stress for example, that is defined as the load divided by the original cross-sectional area of the bar.

The engineering strain is defined as the extension per unit original length. Therefore, the load-extension diagram of a bar with unit cross sectional area and unit gauge length is the nominal stress-strain curve for the material. What I mean to say is that if we have defined that the nominal stress is the load divided by the original cross sectional area of the bar and the engineering strain is defined as the extension per unit original length in that case this load extension curve can be said to be as stress-strain curve.

This is normally you see in the books that these kind of curves are given as stress strain curve. The stress, when considered as acting perpendicular to a surface is called the normal or the direct stress and when parallel to a surface, they are called as shear stresses.

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At any point in a stressed body the stresses may be resolved into nine components acting on the face of an imaginary cube. Let us say we have an imaginary cube like this and this is in a system of axes for example, this is 1, this is axis number 2, this is axis number 3 and this is a stressed body. These stresses may be resolved into nine components. These stresses which are acting as perpendicular, they are the normal stresses or direct stresses let us say 3.

The stresses which are acting parallel to the faces of the cube are called as shear stress this is τ_{31} from 3 to 1 and this is the τ 3 to 2 and here we will have 2 that is this is the τ 2 to 1 and here this stress parallel to the surface which is the τ_{23} . So, as you understand that this will be the τ_{13} and this will be the τ_{12} .

So, there are nine components of stresses which are there and the axes defining the phases like for example, here we have taken 1, 2 and 3 of the cube may be chosen in any direction and for some purpose it is convenient to choose axis so that the shear stresses are 0. In that case the normal stresses acting are called as the principal stresses.

The Mohr circle stress circle construction is a convenient means of relating these stresses on any plane to the principal stress. This is the Mohr circle and the center of this circle will be lying on the direct stress, this is the shear stress. In case of 3D, when we have the 3-dimensional then, let us say principal stresses are σ_2 and this is σ_3 . If we have the 2-dimensional cases in that case this will be shear stress and this is the normal stress and then we have the Mohr circle and we have this σ_1 and this is σ_3 . Any point on the surface will be defined by a point on the Mohr circle. So, this is let us say B point and here it will be inside this. So, this is the point B and this will define the σ_B and this will be defined as the B. So, this is the point which will be on the Mohr circle and this is defining the stress on of a surface.

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Now, suppose the l_1 is the original length of a bar and small l is the current gauge length after the elongation. So, l_0 is being elongated to let us say small l. Then the true or natural strain which is defined let us say by e is defined in terms of the strain increment that is e will be $\int_{l_0}^{l_1} \frac{dl}{l}$; l_0 is the original length of the bar and l_1 is the length after it is elongated. And, $\int_{l_0}^{l_1} \frac{dl}{l} = \ln\left(\frac{l}{l_0}\right)$.

Now, the advantage in using the logarithmic definition of a strain is that the logarithmic strains are additive in sequential process alright, which is not true for the linear stress. Well, what does it mean additive in sequential process? Let me give you an example; suppose, a bar is strained during a tensile test from l_0 to l_1 . The true strain as it is done

here in this case will be, let us say, e' this is logarithm of $\log\left(\frac{l_1}{l_0}\right)$ and this bar from l_1 has been further being elongated to, let us say, l_2 .

The further strain will be in that case will be e'' and this will be $\log\left(\frac{l_2}{l_1}\right)$. So, the total

strain that is coming out to be e' + e'' and this is $\log\left(\frac{l_1}{l_0}\right) + \log\left(\frac{l_2}{l_1}\right)$ and here what we are

getting is $\log\left(\frac{l_2}{l_0}\right)$. So, that is why we are saying that this is a additive in nature alright.

They are being added up and we will be interested only in the final length after being elongated and the initial length.

So, if we take the logarithm and divide the final length after being elongated by the original length we will get the final strain or total strain that is happening. This is not true in the linear strain; when the linear strain happens, they are not actually additive in nature alright. So, this is the advantage.

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Now, let us discuss the mechanism of plastic deformation. Let us try to describe this mechanism in terms of the atomic scale. Let us say that we have the lattice structure like this as it is shown here. By lattice structure you understand that these are the atoms

which are in equilibrium position located in the material. For plastic deformation to occur it is necessary to have large scale slipping, where two planes of atoms slip past each other causing one entire section to move relative to another.

Now, when we have the lattice structure where the atoms are in equilibrium position and if we are applying some strain or stress or shear force, in that case one full layer of atoms will be moving with respect to another layer and if the forces are high enough in that case these layers after being slipped or after being moved they will remain in position. That we are calling as a slip, which is the permanent movement or plastic deformation.

To have large scale slipping, this slip – slip means the movement of one layer with respect to another layer - the slip occurs more easily on certain crystallographic planes depending on the crystal structure – meaning that when you are applying the shear force or shear stress, the atoms are moving. Now, how to find out that which layer will be moving with respect to which layer? Those are called the slip planes and they depend on the materials.

So, slip occurs along the slip planes and crystallographic planes that are farthest apart are also the ones of the greatest atomic density. Now, what we are saying is that when two layers of atom have to move with respect to each other when the shear force or shear stress has been applied, then it will move along the slip planes which are farthest apart from each other and those two layers will have the maximum atomic density.

Let me give you an example. Suppose, we have a material where we have the face centered cube. You are all familiar with the face centered cube. There are BCC, there are FCC. So, let us take an example of the FCC. Here we have atoms like this at each face. Now, in a face centered cube like this you can actually draw a plane like this; this is the plane along which you will find the maximum atomic density, the number of atoms will be maximum. You cannot draw any other plane where these many atoms will be located.

That is the plane of maximum atomic density. Now, if the two layers will have the maximum atomic density then in between the resistance to the plastic deformation will be less or minimum. Therefore, material will be deformed along this plane because it will get less or the minimum resistance to the plastic deformation, because these two layers are farthest apart from each other and these two layers have the maximum atomic density.

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Now, to continue with the mechanism of plastic deformation, let us see how this slip occurs. When two atoms are sufficiently close to each other, the outer electrons are shared by both the nuclei alright. Suppose, there are two atoms here and they are sufficiently close. So, here is the nuclei, here is the nuclei of another atom and here are the electrons which are outer electrons of both of them. So, this outer electron belongs to this atom also the other one belongs to the next atom. Once they are very close to each other, these outer electrons will be shared by both the nuclei.

As a result, there will be an attractive force; attractive force between the two atoms and repulsive force because when two nuclei will be coming closer they will have a repulsive force. As a result when two atoms are very close to each other, they will be attracting each other because these electrons are shared by both the nuclei and then when they are coming closer to each other, they will not collapse because these two nuclei will repulse each other.

So, this is how the attractive force changes; as the inter atomic distance decreases, the force increases; as they are coming closer to each other that attractive force is becoming more. Similarly, this is the curve for the repulsive force and this also becomes more as the inter atomic distance is less meaning if the two atoms are coming closer to each other, they will have more and more repulsive force as well.

So, they will have the attractive force as well as the repulsive force. At this point where the attractive force curve and the repulsive force curve both are crossing each other, in that case, this is the distance which is called the equilibrium distance, meaning, at this distance the atoms are in equilibrium position - they will not be collapsed. They will come to an equilibrium position where the attractive force and the repulsive force both are same.

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We will continue that discussion little later after we discussed these structures. These atoms that we have seen form a polycrystalline solid with atoms in equilibrium position. So, here these are the atoms here and this is the polycrystalline solid and here we have the grains - each grain has the atoms which are located in the equilibrium position.

Now, these polycrystalline solids are not perfect; that means, in the lattice structure there are always imperfections. They are not perfect in the sense that not all the atoms are arranged in the regular way. So, what are those imperfections? These are the imperfections which are known as the point defect, line defect and the surface defect. The point defect is something like for example, in a lattice structure there is one atom missing, here you can see there is no atom. So, this is a defect; this is called a point defect and known as the vacancy because there is one atom missing in the lattice structure.

Similarly, look at this lattice structure, for example. All of a sudden one atom is taking a very odd position in the lattice structure. These are all the regular positions the atoms are taking, but here is the atom which is taking an odd position in the lattice structure and this defect is called as the interstitial impurity. Next is also a point defect. These are all point defects.

Now, the next effect is the substitutional impurity. Here one atom is a foreign atom; in the sense that this atom does not belong to this lattice structure. Somehow it has replaced one of the atoms in this lattice structure. So, this is called the substitutional impurity because this foreign atom is substituting one of the atoms in the lattice structure. So, all these are the point defects and they are actually point defects which are there in poly crystalline solid normally.

Now, apart from the point defects there are also line defects called the dislocation. If an imperfection extending along a line has a length much larger than the lattice spacing; this is the lattice spacing, atomic spacing, so, then that is called the line defect alright. And, when an imperfection is extended over a surface, this is called the surface defect and when the surface defect happens, you understand, it is also called the twinning; that means, the deformed surface is a mirror image of the other surface.

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Now, let us see the elastic and plastic deformation in the atomic scale. So, if you plot the curve of the net interatomic force versus the interatomic distance, this is the line that we

can get. So, the net inter atomic force versus the inter atomic distance can be represented by this curve.

Suppose, there is a point here which is in the equilibrium position. This distance is the d_c ; this is the equilibrium position where the atoms are in the equilibrium, stable in the lattice structure. It has to be this point because here this is intersecting the axis and suppose from here we are moving the atom from here to here and if the distance that we have moved d_A it is not more than 5% of the *d* equilibrium, in that case this will be the elastic deformation.

Once again if d_A this distance after the atom is moved from the equilibrium position here where the curve is intersecting the axis, this is the equilibrium position when the atom is moved from this position to this position and the distance becomes d_A , if d_A lies within 5% of the *de* then upon removal of external forces, the atoms attain their original position. Meaning that if it comes to this point and if this d_A is less than 5% of the *de*, in that case after removal of the force this point goes into this. I mean the atom comes from this position to this position if the force is removed.

What is the force we are talking about? We are talking about the shear force which is causing two planes of atoms to move with respect to one another. And, if this force is not more than 5% with respect to the equilibrium position, in that case it is elastic deformation; that means, if the upon removal of the force the planes are again coming back to the initial position all atoms are again becoming in the equilibrium position.

If d_A becomes more than 5% of the *de* this is actually the equilibrium position. So, let us call it *de* and not the d_c as I said now if d_A becomes more than 5 percent of *de* then upon removal of external forces the atoms do not come back to their original position and as we understand that this is called in the permanent deformation or the plastic deformation. When the two atoms move past each other and they stay in that position upon removal of the external force it will not come back. This is the plastic deformation.

This is how we can actually understand the elastic or plastic deformation in the atomic scale when we know that in a lattice structure the layers of atoms they move or slip past each other which is called the deformation. Now, this deformation can be either elastic deformation or plastic deformation. As we said that elastic deformation happens when it

is linear; that means, the load and the extension curve is linear and if it is non-linear beyond of course, yield point this is the plastic deformation.

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Mechanism of Plastic Deformation The amount of Shear Stress necessary to effect the Slip: ; for small values of $\binom{x}{-}$, it can be Let us assume, $= \tau_0 \sin($ expressed as $= G\left(\frac{x}{b}\right) \quad or, \tau_0 =$ In practice the shear stress required is much less

Now, let us see the amount of shear stress which is necessary to affect the slip; that means, how much we want that a shear force so that the layers could be permanently moved or permanently slipped along the slip plane alright. Let us say these black lines are the atoms which are in the initial position and because of the shear stress which is applied to the lattice structure to the material, the atom has moved from this position to this position which is *x*. *x* is the movement of the atom because of the application of the shear stress τ .

Now, the distance between the two layers is *b* and the distance between the two atoms that is the inter atomic distance, this is let us say *a*. So, in that case within the *a* - within the inter atomic distance the movement of the atom that is the *x* can be represented by this curve where the τ_0 is the maximum shear stress which is being applied so that this movement takes place and then it goes in a sinusoidal way.

Once again this is a lattice structure and initially that was in the equilibrium position. Then, there is a shear stress which is being applied to the lattice structure and because of that the atoms are moving from this equilibrium position to another position and this movement is let us say x. So, within that interatomic distance the atom will be moving

like this where τ_0 is the maximum shear stress which is required to cause that slip. This we are causing at the slip; that means, the movement of the atom from the equilibrium position is the *x*.

Now, we will define what should be the value of the τ_0 , that is the maximum shear stress that has to be applied to affect the slip in our next session.

Thank you very much.