Mathematical Modeling of Manufacturing Processes
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Lecture – 11
Heat Transfer Analysis

Hello everybody, now I will start the second part of this conventional machining process. So that is the heat generation in machining processes.

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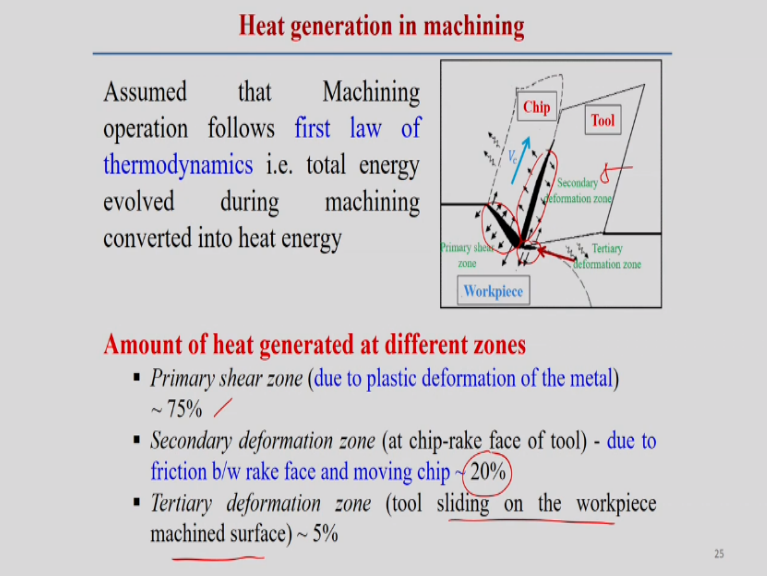

Heat generation in machining

Assumed that Machining operation follows first law of thermodynamics i.e. total energy evolved during machining converted into heat energy

Amount of heat generated at different zones

- *Primary shear zone* (due to plastic deformation of the metal) ~ 75%
- *Secondary deformation zone* (at chip-rake face of tool) - due to friction b/w rake face and moving chip ~ 20%
- *Tertiary deformation zone* (tool sliding on the workpiece machined surface) ~ 5%

So if we look into that chip generation from here the actually the tool is moving which tool is in contact with workpiece the shear plane where the shear zone, there is a shear deformation happens and that actually transformation from the solid workpiece in the form of the chip and the chip is just goes out through the rake face of the tool.

So if we assume that first law thermodynamics that means all mechanical energy basically we are putting the all mechanical energy is converted to the heat energy and based on that we can define the three different zones where we can find out the mechanical energy is basically converted to the heat energy.

First is the primary shear zone or we can say the primary deformation zone. So at this point primary shear zone maximum heat generation normally happens at this part. So we can approximately we can say that 75% of the heat and that is due to the plastic deformation happens in this process. So of course plastic deformation happens but plastic recovery part is very small in this cases.

And secondary deformation zone, that secondary zone that what the next amount of the heat generation normally happens that is the between the chip and the tool face and due to the friction and because over the rake face the chip actually flows. So the frictional heat generation normally happens at this zone that is called the secondary deformation zone.

And the third deformation zone which is in contact between the tool and the workpiece, in that part the heat generation is very small actually it is account maybe approximately 5% and because the tool actually slides over the finished workpiece sliding on the workpiece and on the machine surface that because of that some amount of the heat actually generated at this point but that heat generation part is very small.

And secondary deformation zone, we can account that only 20% of the heat is normally generated at this part. Now apart from this heat generation maybe you can neglect the third zone where the between the tool and the workpiece, workpiece means the machine surface that part heat generation is very small so we can neglect that part.

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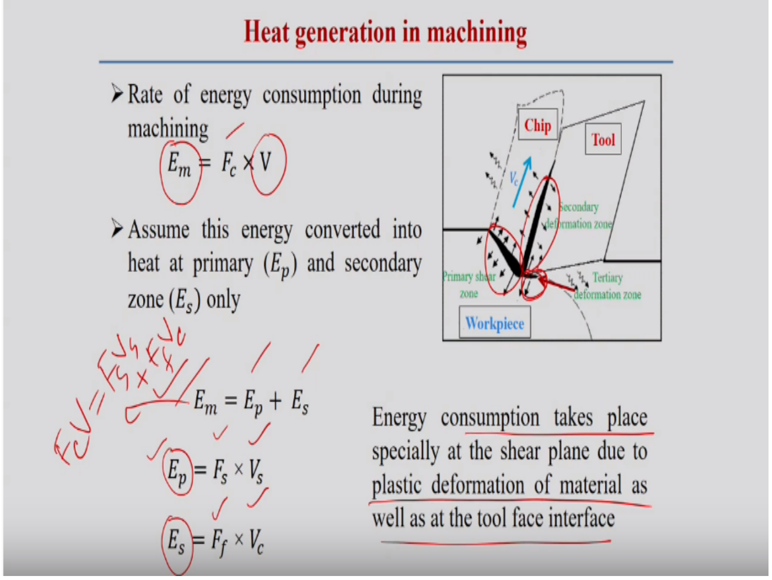

Heat generation in machining

- Rate of energy consumption during machining

$$E_m = F_c \times V$$

- Assume this energy converted into heat at primary (E_p) and secondary zone (E_s) only

$F_cV = F_sV_s + F_fV_c$

$$E_m = E_p + E_s$$

$$E_p = F_s \times V_s$$

$$E_s = F_f \times V_c$$

Energy consumption takes place specially at the shear plane due to plastic deformation of material as well as at the tool face interface

But what we can estimate the power energy consumption or maybe energy required during this process machining process what we can estimate mathematically. So first we look into that what is the tool force we already estimated that energy rate of energy consumption during the machining process that overall if we know what is the cutting force Fc and what is the velocity vector along the direction of the cutting force.

That is the velocity V and that velocity V is the relative velocity between the workpiece and the tool or maybe that velocity either we provided with the tool material or we can provide to the workpiece material. So that force into velocity that estimates the amount of the energy input to the during the machining process or we can say the amount of the energy required during the machining process.

But this energy input energy is basically converted to the heat energy that is the primary deformation zone and mainly the secondary deformation zone. We neglect the third one that may be the third zone that between the tool and the workpiece of this miscible on the machine surface that part we can neglect it here. And we assume that total energy input is converted to the in the primary at the primary deformation zone and at the secondary deformation zone.

We can make the balance, energy balance like that Em=Ep, the primary deformation zone. Energy is converted to the heat energy and the secondary deformation energy converted to the heat energy because of the friction. So energy consumption takes place but if we see then this note the specifically at the shear plane. So maximum energy actually heat generation normally happens at the shear plane due to the plastic deformation of the material.

And next if we see the next zone that is the secondary deformation zone that means between the chip and tool workpiece. Now we can make this balance energy balance of course this energy balance neglecting the energy generated at the third zone. So this energy consumption the primary deformation zone, we can easily estimate if we know the shear force Fs and of course the velocity.

We have already discussed how to estimate or maybe shear force or this shear force can be a function of the two major components of the cutting forces we can measure it and we can estimate the shear force. And of course from velocity triangle it is possible to define or estimate the shear velocity. So this is the primary deformation zone and that is the secondary deformation zone.

In the secondary deformation zone, this is the frictional force and of course which direction we are taking the frictional force along this direction what is that velocity basically chip velocity that was we can estimate. So this chip velocity can also be estimated from the velocity triangle that we have already discussed about this thing. So we can easily estimate this total energy which is Fc x V.

So then make a energy balance FsxVs + FfxVc chip velocity. So all in terms of the velocity and force components we can roughly make the energy balance and we can do further energy, we can estimate the energy consumption during the machining process. Of course this machining process corresponds to the orthogonal situation.

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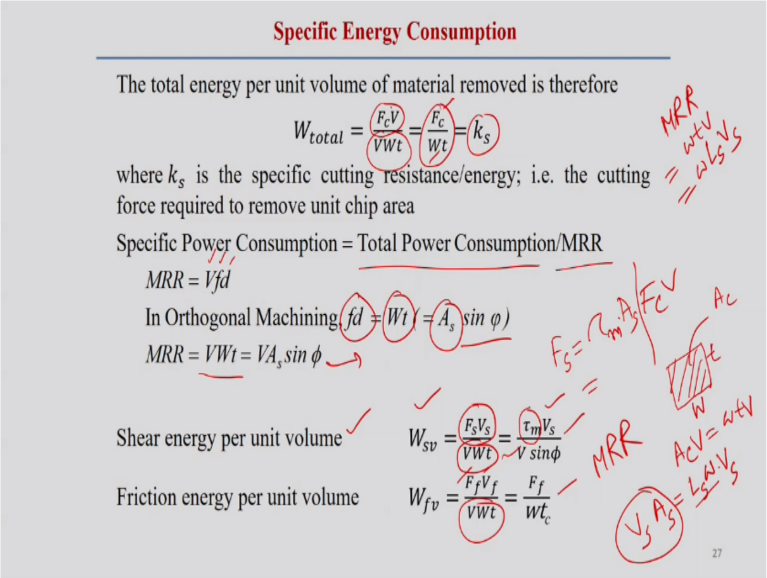

Specific Energy Consumption

The total energy per unit volume of material removed is therefore

$$W_{total} = \frac{F_c V}{VWt} = \frac{F_c}{Wt} = k_s$$

where k_s is the specific cutting resistance/energy; i.e. the cutting force required to remove unit chip area

Specific Power Consumption = Total Power Consumption/MRR

$MRR = Vfd$

In Orthogonal Machining, $fd = Wt\ (= A_s \sin \varphi)$

$MRR = VWt = VA_s \sin \phi$

Shear energy per unit volume $\quad W_{sv} = \frac{F_s V_s}{VWt} = \frac{\tau_m V_s}{V \sin\phi}$

Friction energy per unit volume $\quad W_{fv} = \frac{F_f V_f}{VWt} = \frac{F_f}{wt_c}$

Now this term terminology is also important practically to estimate the specific energy consumption. So specific energy consumption we understand that specific energy consumption means per unit volume flow rate basically what is the energy consumed in this case. So we estimate that Fc x V is the total energy input during the machining process with required amount of the energy or maybe we can if we look into that Fc x V force into velocity that means energy per unit time actually this indicates the energy per unit time here.

Now if we divide the volume flow, volume flow rate basically during this process. So volume flow rate means you know the area of the cross section we assume if we uncut chip thickness t and width of the chip W. So this is the area of the cross section so it can be say area of the cutting. So now velocity vector normal to this area of the cross section Ac x V that indicates the per unit time what is the volume of the metal actually removed. So it seem to be or we can say Wt x V.

So this way we can estimate the volume flow rate. Of course volume flow rate can also be estimated or maybe volume from other also if we know the cross section area on the shear plane so there also we can estimate the I think length Ls shear plane length this and width of the chip W if we assume there is no change width of the chip and of course if we know the velocity vector.

So this Vs should be perpendicular to the area of the cross section. So here also we can estimate this is the As=LsxWxVs and that Vs so that indicates VsxAs is the volume flow rate during the machining process or material removal rate we can say that this circle MRR. So MRR can be represented that MRR either WtxV or so=if we assume there is no t, the shear plane and shear velocity.

So if you note any information then with uncut chip thickness or cutting velocity or other we know the shear velocity we can easily estimate the material removal rate in terms of the volume flow rate. So that Fc if we see FcV the per unit volume material removal rate if we see the Fc/Wt that indicates the specific energy cutting energy or cutting resistance that means the cutting force required to remove unit chip area.

So this indicates that what is the cutting force required to remove the unit chip area that indicates the specific energy in this case. So specific power consumption can be or can be estimated the total power consumption divided by material removal rate. Of course material removal rate also can be estimated in other parameters in case of orthogonal machining processes. So V is the cutting velocity feed rate and depth of cut.

So feed rate and depth of cut which is analogous to the width of the cut and thickness of the chip. Also it is equivalent to As x sin phi in terms of the shear angle. Then material removal rate can be estimated VWt or VAs sin phi these two we can estimate or if feed rate and depth of cut is known to us then we can estimate the material removal rate in this case. But of course it is a this material removal units should be the volume per unit time basically volume per unit time.

Similarly shear energy per unit volume can also be estimated like that this is the shear energy or maybe per unit time and this is the material removal rate and that can be estimated like that because shear energy, the shear stress into shear force area and that is equivalent to that into basically the shear stress is basically we can estimate the shear stress into shear area. So then if we put the shear area value we can estimate that it is Vs/V sin phi.

Similarly, friction energy per unit volume also estimated that this is frictional energy force into velocity and that is the material removal rate and from there we can estimate the specific energy due to the friction or specific energy due to the shear. All this can be estimated during this machining process.

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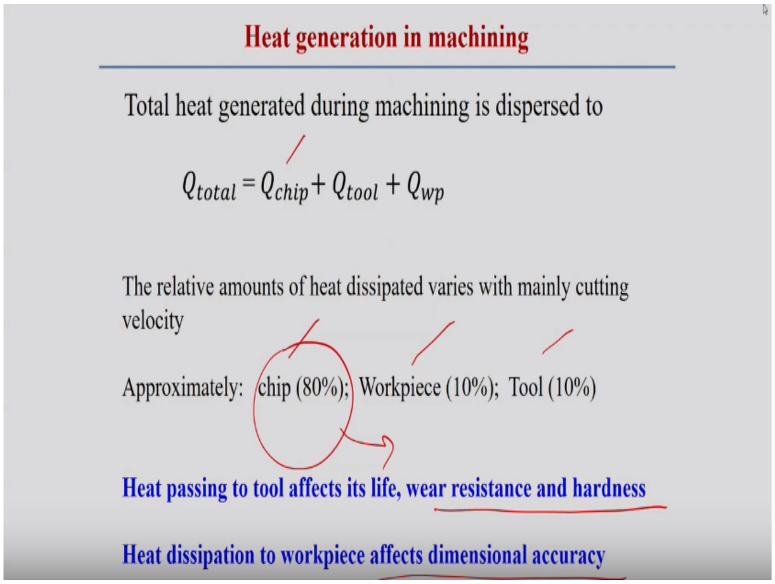

Heat generation in machining

Total heat generated during machining is dispersed to

$$Q_{total} = Q_{chip} + Q_{tool} + Q_{wp}$$

The relative amounts of heat dissipated varies with mainly cutting velocity

Approximately: chip (80%); Workpiece (10%); Tool (10%)

Heat passing to tool affects its life, wear resistance and hardness

Heat dissipation to workpiece affects dimensional accuracy

Now since we estimate the heat energy generation total heat energy generation at the different primary deformation zone, secondary deformation zone and third deformation zone in this cases. Similarly, there is a heat generation the heat will be dissipated and of course the heat will be dissipated at the different zones the response may be in the terms of the temperature. So that subject area or that components may be subjected to some temperature rise during the machining processes.

Because there is a generation of the heat. Now if we assume that total energy generation during the machining process due to the energy dissipated because the outcome from the machining processes the energy can be dissipated through the chip, energy can be dissipated to the workpiece and some of the amount of the energy can be dissipated to the tool material because all are in contact during this machining process.

Now if we roughly estimate that what is the amount of the energy dissipated at the different medium may be approximately chip carry the approximately 80% of the energy, workpiece carry around 10% of the energy and tool also carry around 10% of the energy heat energy during this process. So of course when there is a this chip, workpiece, and tool that carry the different ratio of the energy during this process of some temperature rise must be there.

But if it is possible to reduce the amount of the energy carried by the tool then it will be beneficial in the sense, the life of the tool can be increased. Because the temperature generation on the tool material actually affects its life and of course it accelerate the wear, wear during this process.

So if we want to improve the wear resistance properties and we want to keep the hardness even at very high temperature. Then this is as minimum as possible to amount of the energy should be carried out by the chip or we can restrict the temperature generation or maximum rise of the temperature on the tool material.

Similarly, heat dissipation to the workpiece if large amount of the heat energy dissipated or there is a high temperature rise during the machining process to the workpiece machine workpiece material then it affects the dimensional accuracy of the machine component. So therefore if we want to obtain a very good finish though there also try to minimize the amount of the heat energy or try to minimize the temperature rise to the workpiece material.

So it will be always beneficial the maximum and amount of the energy or maximum temperature rise to the tool material or sorry to the chip material what are the chip formation. So that is the objective to enhance the amount of the maximum energy to be carried out by the chip.

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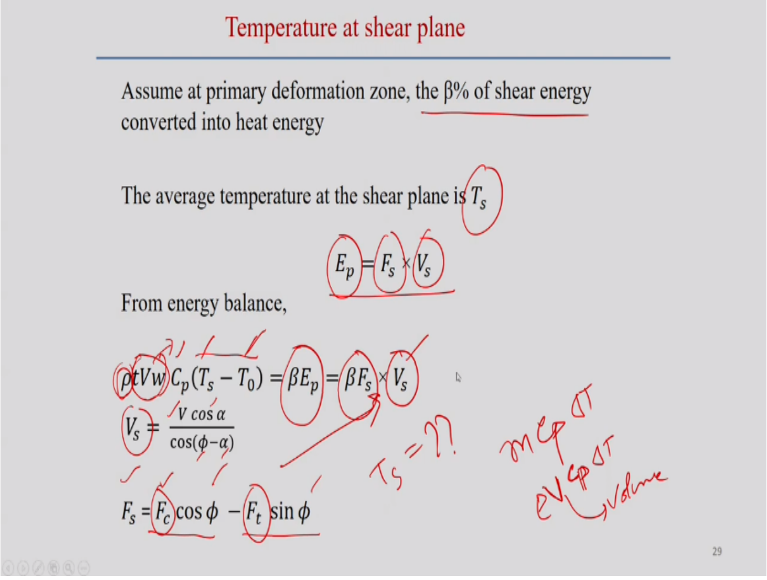

Temperature at shear plane

Assume at primary deformation zone, the β% of shear energy converted into heat energy

The average temperature at the shear plane is T_s

$$E_p = F_s \times V_s$$

From energy balance,

$$\rho t V w C_p (T_s - T_0) = \beta E_p = \beta F_s \times V_s$$

$$V_s = \frac{V \cos\alpha}{\cos(\phi - \alpha)}$$

$$F_s = F_c \cos\phi - F_t \sin\phi$$

$T_s = ??$

$m C_p \Delta T$

$\rho V C_p \Delta T$

volume

Now roughly we can estimate what is the temperature rise at the shear plane and from the point of the energy balance or if we assume the some amount of the energy. We can estimate what is the energy consumption during a shearing of the material in the machining processes. If we assume the at the primary deformation zone to the shearing normally happens. We assume that beta percent of the shear energy. So that percent of the shear energy actually converted into the heat energy.

Now if we assume that average temperature rise or average temperature reach at the shear plane is basically Ts suppose we assume this is the average temperature the Ts. So what is the energy consumption during the in the primary deformation zone, the heat energy is simply estimated by the shear force and the shear velocity Fs and Vs so from here. Now if we look into the energy balance so we assume not all the energy is converted to the to enhance the temperature rise of the things.

So certain percent of the energy may be actually utilize to enhance the temperature rise. So if we look into the energy balance so if we assume this amount of the energy beta into Ep is actually utilize to enhance the temperature of the shear plane beta. So that can also be estimated beta FsxVs. Now we make the energy balance in other suppose this is the final temperature of the shear plane average temperature.

And then T0 is the initial temperature, we can say the ambient temperature. So we know that that m, the heat content during the mCp delta T these cases but here m=m=Rho into volume Cp delta T in the heat content particular process. Now Rho is there and tV and w that actually represents the this is actually volume. So that volume that means here volume consumed or volume per unit time that is equivalent to the MRR material removal rate.

So that indicates the volume but this is per unit time and the specific heat and this is the temperature rise and the right side also the energy consumption that means the energy consumption per unit time. So then if we both make it equal, we can easily estimate the what is the Ts from this expression.

So but if we look into the from this expression so Vs the shear velocity Vs we can easily estimate from the velocity triangle there in terms of cutting velocity, the tool geometry angle alpha and cos phi - alpha shear angle and the rake angle. From here we can easily estimate that Vs. Fs shear force, shear force can also be estimated in terms of the from the Merchants circle diagram.

We can estimate Fc cos phi - Ft sin phi, if shear angle is defined and Fc if we know Fc and Ft component that the cutting force components during the machining process we can easily estimate what is the shear velocity. Once we know the shear force component. So once we know the shear force components and if we know the shear velocity and we put it here.

And from here this is the specific of the material that we know the specific of the material is well defined quantity, material removal rate we needs all this data and density also material properties and T we assume the ambient temperature any ambient temperature. From here we can assume in terms of the other parameters we can easily estimate what is the average shear plane.

So this is a rough estimate we can get some idea what may be the average temperature in shear plane during the machining process.

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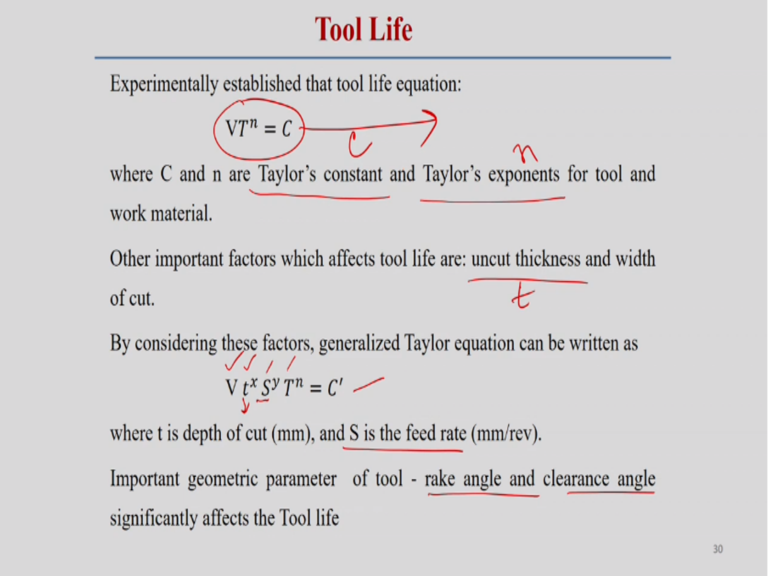

Tool Life

Experimentally established that tool life equation:

$$\boxed{VT^n = C} \longrightarrow C$$

where C and n are Taylor's constant and Taylor's exponents for tool and work material.

n

Other important factors which affects tool life are: uncut thickness and width of cut.

t

By considering these factors, generalized Taylor equation can be written as

$$V\,t^x\,S^y\,T^n = C'$$

where t is depth of cut (mm), and S is the feed rate (mm/rev).

Important geometric parameter of tool - rake angle and clearance angle significantly affects the Tool life

Now we come to that point tool life is one important parameter but what we can measure life of the tool it is economically it is a very important aspect to consider the life of the tool during the machining process. So it is experimentally observed that actually the tool life is the mostly depends and the life is mostly is in terms of the most influencing parameter is the velocity component here.

So tool life mostly as a largely as a function of cutting velocity and loosely depends on the other parameters as well also but experimentally observed this is the VT to the bar n=constant C. So this is empirically related between the life of the tool T which is over represent in terms of the minute here and V is the cutting velocity I think cutting velocity millimetre per minute and then T is the life and n and C are the constants.

That is called the Taylors constant and Taylors exponent that is n and Taylors constant=C for tool and the workpiece. So this C and n value is actually is a fixed is a particular value that depends on the tool and the workpiece material combination. Now this is the well-established and well known Taylors tool life equation and this is widely used still to estimate the life of a particular tool.

And of course this value C and n varies depending upon the different types of the tool material. And of course we assume that tool material what type of workpiece material we are engaging to cut. But apart from this velocity components the tool life also influenced by the uncut thickness what are the thickness we are supposed to cut during the machining process and width of the cut that also other important parameters that decides the life of the tool.

If we consider the effect of the uncut thickness and width of the cut then Taylors tool life equation can be modified in this way also Vt to the power x, S to the power y and T to the power n and this here small t is the thickness uncut thickness and width of the cut, S is the feed rate and T is the T is the life of the tool. So here we can that we can modify this equation and C dot is a constant.

But of course the depth of cut is more important here and depth of cut and feed rate is more important here rather than the only the width of the cut. So list preference is given to estimate the tool life that is the width of the cut. So other geometric parameters of the tool that is the rake angle, clearance angle also significantly affect the tool life that they can but it is very difficult to introduce in the mathematical form the effect of the geometric parameters of a tool.

Because we have already explained that what is the effect of the different angle because this tool rake angle, clearance angle significantly affect the tool life in the sense that they actually influence the strength of the tool as well as the heat dissipation capacity during the tool that largely depends on the tool rake angle and the clearance angle. So that is the secondary parameters that influence the life of the tool.

But in general we understand this is the most Taylors tool life equation that most important parameters to decide the tool life is the velocity components. But how it behaves this tool life equation.

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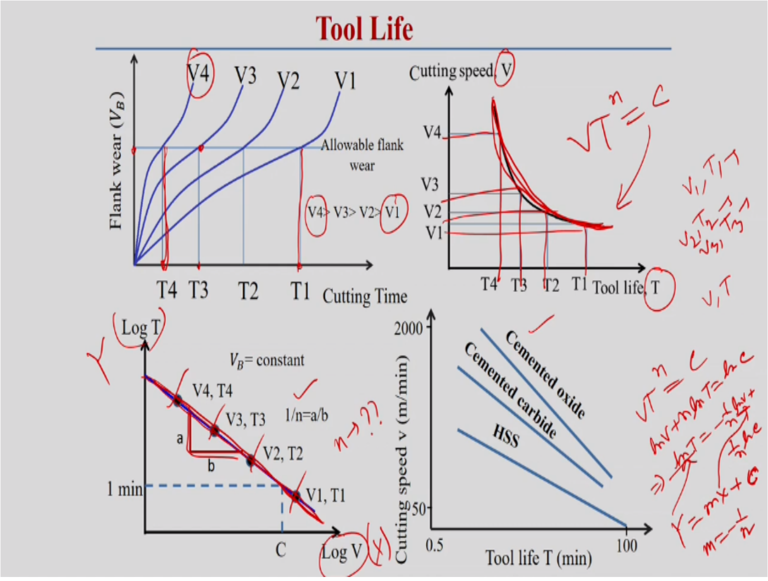

Tool Life

We can see the different graphically we have tried to understand that it is a VT to the power n=constant if it represented graphically. Suppose x-axis represent the tool life, time component and y-axis represent the cutting velocity or cutting speed. Then VT to the power n is the typical nature of this kind of graph. Such that any V4 T4, V3 T3, V2 T2, V1 T1 that finally and to the power n such that it maintain th=constant.

Similarly, when we practically define the tool life then we need to look into the different wear parameters, parameters of a particular tool. Now flank wear of a tool material if we decides the limit or we can accept the tool up to a particular amount of the flank wear that is suppose this is the flank wear is define particular along this axis and suppose this is the cutting time.

Now the life of the tool is basically is the T4 of a particular tool life of the tool if we decides the if we define the limit of the flank wear. So life of the tool will be the T4 if we use the tool for the cutting at velocity V4. And of course in this cases V4 is the maximum velocity. Similarly, the life of the tool can be more T3 if we use the tool at a particular velocity V3. so of course V3 is less than V4.

Similarly, if we can life of the tool can be more T1 if we use the tool at the particular velocity V1 so here the V1 the least velocity. So in general from this equation we can say that the life of the tool can be enhanced if we utilize the tool relatively low velocity. But life span, tool life span can be very small if we utilize that tool as a very high velocity. So that is the impact of the it is a very impact of the velocity on the life of the tool.

Similarly, if we know VT to the power $n=C$ so here we can how to find out the exponent from the experimental data and suppose we have a combination of the V different V and T if we measure the T. Suppose this X is equal we will take the logarithm both side $lnT=lnC$ so from here we can say that $lnT=-1/n \; lnV+ 1/n \; lnC$. So this is $Y=mx+C$, if we use this equation in a logarithm scale so m is basically $-1/n$.

So negative slope we can use in the within the logarithm scale if we use the Y is equivalent to lnT, so this is the lnT. This is corresponds to the Y and this is corresponds to the X. If it is like that in the logarithm scale and X is corresponds to the lnV but 1/n it represents the slope of this curve but about the logarithm scale. So we have suppose we have done a lot experiments and we make a different combination V1, T1 at the different velocity we can measure the V2, T2, V3, T3 the different combination velocity.

And we measure the what is the cutting velocity or what is the life of the tool and if we convert if we put plot this data on a logarithm V on this axis we convert it to in the logarithm scale and if we put it then it represents a straight line and then if we fit the straight line the slope of this curve if we see the slope of this curve that actually represents the from there if we estimate the slope and from here we can estimate what is the value of n actually. From the slope we can estimate the value of n that coefficients.

And of course if we see that this slope here the straight line of this straight line actually it represents the negative slope. So that is why from the negative slope we can from here we can estimate value of the n. So that means that if we have the data at the different experimental data and if we try to fit the data on the logarithm scale and we fit try to fit the straight line from the different points so.

And then from this when you fit a straight line and we measure the slope of this straight line and from that slope we can estimate what is the value of n of a particular such a particular tool material tool workpiece interaction. So this way we can estimate the value of n then similarly if we look into the cutting speed different cutting speed. So life of the tool it is clearly observe we can observe from here that X-axis represents the tool life and Y-axis represents the cutting speed.

So here we can see the cemented oxide, cemented carbide and HSS tool high speed steel tool. So basically all this tool material if we use it, cemented oxide can be used more effectively at relatively high cutting velocity as compared to the HSS and cemented carbide tool.

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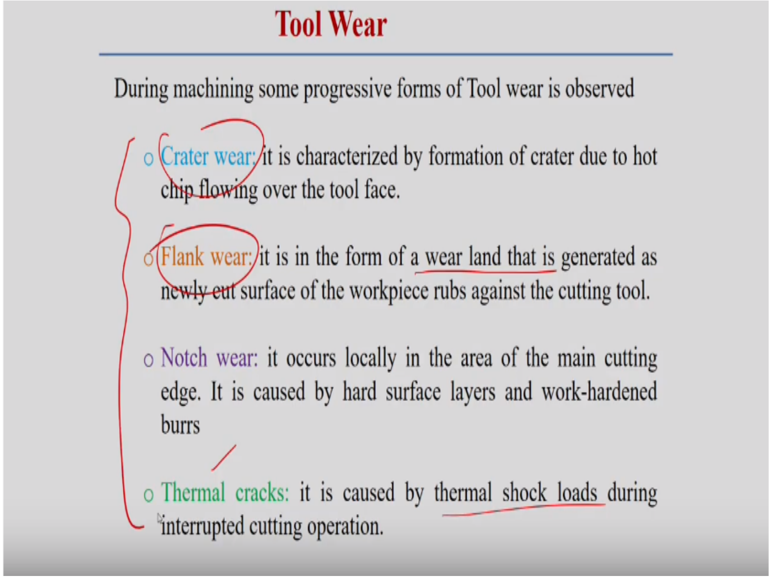

Tool Wear

During machining some progressive forms of Tool wear is observed

- Crater wear: it is characterized by formation of crater due to hot chip flowing over the tool face.
- Flank wear: it is in the form of a wear land that is generated as newly cut surface of the workpiece rubs against the cutting tool.
- Notch wear: it occurs locally in the area of the main cutting edge. It is caused by hard surface layers and work-hardened burrs
- Thermal cracks: it is caused by thermal shock loads during interrupted cutting operation.

Similarly, I can define the tool wear also, so during machining process there are different types of the tool wear we can observe then that is the that we can measure also. One is a crater wear I would say formation of the due to the hot chip flowing over the tool face. Basically crater wear we can find out over the tool face because the chip forms and temperature of the chip becomes very high and that chips actually flow over the a rake face and that creates kind of the crater wear and that we can measure it.

Similarly flank wear on the flank face basically the when the tool actually rubs against the workpiece and against the cutting tool rubs against the cutting tool workpiece. So in that in that cases in the wear land is formed as the newly on the because of the newly cut surface of the workpiece and that is called the flank wear. And the flank face we can find out the flank face of the tool we can find out the flank wear normally happens.

Notch wear locally in the area of the main cutting edge. So notch wear is very localized area it forms and that happens normally in the cutting edge and this is because of the hot surface layers and the work-hardened burrs because when the plastically deform the material becomes work-hardened. So because of the work-hardened burrs then in some localized area notch wear can also be observed.

Of course thermal cracks may also happen. Thermals during the thermal shock loading during the interrupted cutting operation that is why we always prepare to go continuous chip. If there is a discontinuous chip we can say a kind of interrupted cutting operation may happen in certain cases. So that is subjected to most of the cases a kind of thermal shock loading. So in that cases these thermal shock loading creates kind of the thermal crack within the tool. Also this is can be categorized as a tool wear. So all we can measure during this process.

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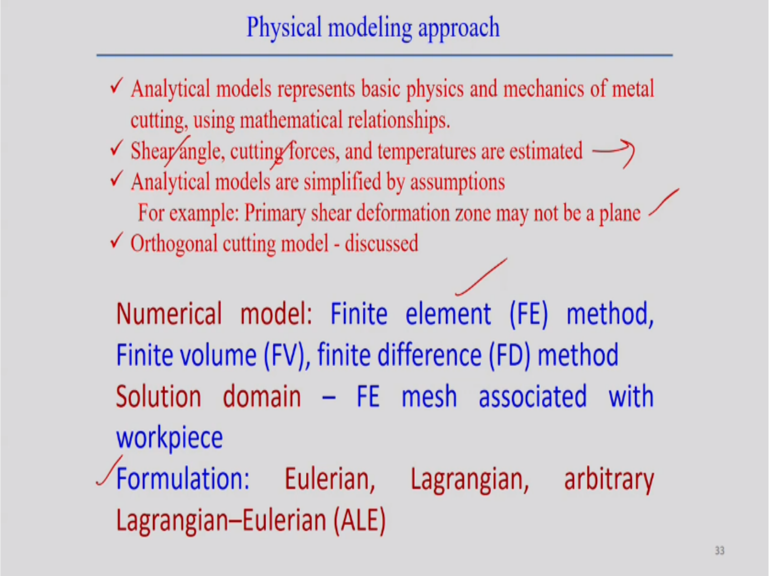

Physical modeling approach

- ✓ Analytical models represents basic physics and mechanics of metal cutting, using mathematical relationships.
- ✓ Shear angle, cutting forces, and temperatures are estimated
- ✓ Analytical models are simplified by assumptions
  For example: Primary shear deformation zone may not be a plane
- ✓ Orthogonal cutting model - discussed

Numerical model: Finite element (FE) method, Finite volume (FV), finite difference (FD) method

Solution domain – FE mesh associated with workpiece

Formulation: Eulerian, Lagrangian, arbitrary Lagrangian–Eulerian (ALE)

Now so far we have discussed that analytical model and orthogonal cutting situation how we can represents the basic mechanics basic mechanism of the cutting process and we can relate different force components and we can easily forms the Merchants circle diagram under equilibrium condition and we can find out the force components using some kind of mathematical relationships. So definitely we assume we can relate the shear angle cutting force.

And of course we can estimate the temperatures can also be estimated with some analytical simple analytical solution but of course it is always true that analytical solution is always there but there are so many assumption simplified assumptions are there. For example, we assume the primary shear deformation zone and then we assume it is a plane but actually it is not a plane there is a zone particular zone the deformation happens and mostly the primary deformation where the maximum heat is generated during this plane.

So that is the one kind of assumptions and from based on this assumption we can find out all this analytical solution. And of course we have discussed so for the orthogonal cutting model but of course in oblique cutting situation that it is very difficult to find out the analytical solution and even it is very difficult to find out analytically estimate the temperature during the machining process.

So in practical in actual problem of the machining always we look for the some kind of the numerical solution and of course once we look into the numerical solution of a particular problem they need to develop the numerical model. So numerical model or numerical modelling techniques mostly developed using either finite element method, finite volume method or finite difference method.

Of course there are other numerical techniques also exist. But mostly development happens in this area the finite element using finite element method for the modelling of physical modelling of the metal cutting process. But before modelling approach we need to define the solution domain to fix and once we decide the solution domain then discretization of the domain is necessary. So discretization by creating the mesh.

And once we define the solution domain and then discretize this solution domain in the form of the mesh. Then we need to look into the formulation or approach we follow to solve the physical problem specifically to the metal cutting process. So there are three approaches Eulerian approach, Lagrangian and arbitrary Lagrangian-Eulerian so that is called normally as ALE method.

Eulerian approach and Lagrangian method. So let us see look into what are the different approaches.

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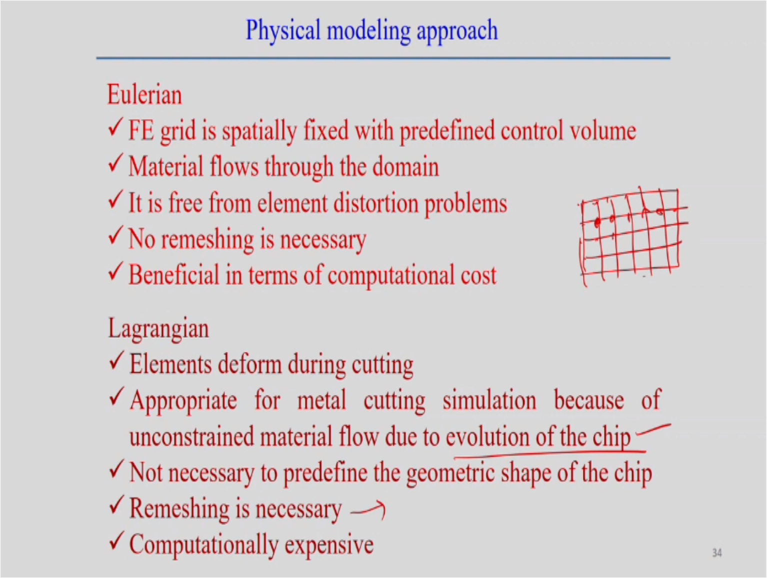

Physical modeling approach

Eulerian
- ✓ FE grid is spatially fixed with predefined control volume
- ✓ Material flows through the domain
- ✓ It is free from element distortion problems
- ✓ No remeshing is necessary
- ✓ Beneficial in terms of computational cost

Lagrangian
- ✓ Elements deform during cutting
- ✓ Appropriate for metal cutting simulation because of unconstrained material flow due to evolution of the chip
- ✓ Not necessary to predefine the geometric shape of the chip
- ✓ Remeshing is necessary
- ✓ Computationally expensive

Eulerian approach, in this case the solution domain we fixed and we mesh it but the grid size is spatially fixed and with the predefined control volume. So volume or the solution domain is basically predefined and within this domain there is a flow of the material may also happen or flow of the chip in metal cutting flow of the chip happened through this domain. But it is a free from any element distortion problem.

So in this process not allowed to distortion of the element. So therefore no remeshing so it is necessary in these cases. And of course this is very as compared to the other approaches this is more efficient in the sense that computational cost is low as compared to the other approaches. So it is like that if we define the solution domain discretize the domain and we try to find out the solution variable at the each node point.

But without allowing this the distortion and deformation of the node point. So since it is not allowing the deformation of the node point so then may be remeshing is not necessary in this process. Then what we can estimate the field basically in particular for it is basically a static domain and that domain we try to find out what is the velocity components or maybe strain rate at a particular node point.

So two approaches can be formed if we estimate the if the chip velocity is there if we estimate the velocity components of the chips either solid mechanics approach or fluid dynamics approach. If we look into the solid mechanics approach then we estimate the strain and we can find out what is the strain rate at the particular node point without allowing the deformation of the node. So that is the Eulerian approach.

In Lagrangian approach so we allow the elements deform during the cutting if we allow some deformation but this is more appropriate in the metal cutting simulation because unconstrained material flow normally happens during this process specifically during the metal happen during this process means the during the evolution of the chip. Now in this cases it is not necessary to predefined the geometric shape of the chip.

So we just track what is the chip of the see we track the because since there is we there is no constraint to following up of the deformation of the chip. So we track the chip and allowing the deformation of a particular node point. But periodic remeshing is necessary in this approach so once deformation becomes very large or maybe we can remesh that solution geometry and then start the solution up early meshing on this thing.

So of course during the transport of the of all variable after remeshing. So in this cases that it is becomes very computationally very expensive and computationally it is very computational cost is very high in a Lagrangian approach. But of course in terms of modelling precision all this thing it is a better solution we can expect from the Lagrangian approach as compared to the Eulerian approach.

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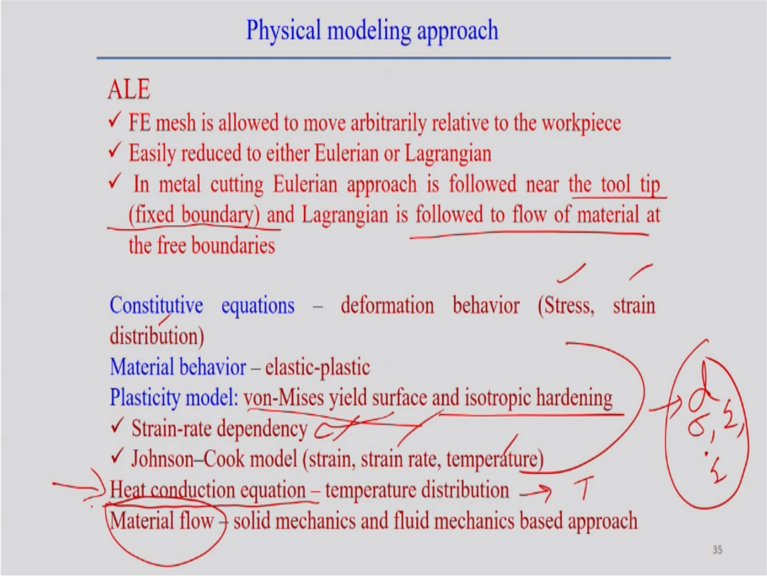

Physical modeling approach

ALE

- ✓ FE mesh is allowed to move arbitrarily relative to the workpiece
- ✓ Easily reduced to either Eulerian or Lagrangian
- ✓ In metal cutting Eulerian approach is followed near the tool tip (fixed boundary) and Lagrangian is followed to flow of material at the free boundaries

Constitutive equations – deformation behavior (Stress, strain distribution)

Material behavior – elastic-plastic

Plasticity model: von-Mises yield surface and isotropic hardening

- ✓ Strain-rate dependency
- ✓ Johnson–Cook model (strain, strain rate, temperature)

$\rightarrow \sigma, \varepsilon, \dot{\varepsilon}$

Heat conduction equation – temperature distribution → T

Material flow – solid mechanics and fluid mechanics based approach

There is another approach that is called ALE approach in machining process we use. So in this cases that FE mesh is allowed to move arbitrarily with respect to the workpiece material. So ALE approach since ALE approach the combined beneficial from the Lagrangian and Eulerian approach in this cases. So it is necessary it is we can easily shaped the either Eulerian or we can reduce the approach either Eulerian or Lagrangian whenever necessary.

For example, in the metal cutting and the near the tool tip. Near the tool tip because tool is almost hard material we assume if the tool is rigid material and we do not allow deformation of the tool. So in that cases the Eulerian approach is possible because there is a fixed boundary. So in that case we can easily use at that part the Eulerian approach. But similarly if we want to track the chip deformation and the flowing of the chip then we can use the Lagrangian approach.

Because in Lagrangian approach the boundary there is no constraint within the boundary so chip can flow it is a free boundary and chip can flow different accordingly. So when we try to make the simulation of the chip formation in that case we can we can assume the Lagrangian approach to model this flow of the chip.

So of course when you try to model these things so normally model means in metal machining process we try to know what is the stress distribution, heat transfer, temperature distribution as well as the deformation behavior of the machining process so that we try to model. But we need to know some constitutive equation when we try to model we try to analyze the deformation behavior of the metal cutting process.

So deformation behavior what we can represent the deformation behavior. Deformation behavior, we can find out what is the displacement in a particular point we can predict the displacement field but that displacement can also be estimated in terms of the stress relate and in the strain distribution. But we need to know the constitutive relation exists between the stress and strain.

And of course how we can convert the displacement field into the strain field and in this case the material behavior we can assume the elastoplastic material behavior perfectly plastic material we can assume the viscoplastic material we can assume if we assume the viscoplastic material behavior then we can predict the velocity field. Velocity field in terms of the strain rate during this machining process also.

And of course we can assume the material behavior, elastoplastic metal behavior of a machining process. In this case, we need to consider the elastic recovery of this process but elastic recovery is very negligible. So then we can assume the very perfectly plastic material. Of course once we look into then elastoplastic behavior then we need to know the how to decide the yield criteria because in the elastoplastic material behavior we need to transition from the elastic to the plastic zone.

So there we need to define the yield surface and that yield surface and of course once across the yield surface what are the different type of the hardening model we should allow during this process. We need to know normally we use the von-Mises yield criteria to decide the yield surface and of course the hardening behavior is a isotropic hardening it may be the kinematic hardening depending upon the problem itself.

And of course there is the other option also whether we can the hardening all this thing and whether we can is a strain-rate independent process or strain-rate dependent process also. So in this cases the kinematic modelling will be very complicated if we use this the strain-rate dependency. Apart from the other plasticity model can also be used that is normally used in Johnson-Cook model.

But in Johnson-Cook model if the material model itself is a function of strain-rate and temperature all this variable. So you need to define strain, strain-rate and temperature for this Johnson-Cook model. So from here we can predict the displacement field, stress field and strain field and if we estimate the strain field of course we can estimate the strain rate field. All are important outcome from the deformation behavior.

If we analyze the deformation behavior or we try to convert into terms of the model. Now apart from that of course distribution of the temperature is also important because if we know the temperature distribution then we can estimate the thermal strain, strain gradient exists within the domain from here from the thermal strain. We can predict the deformation behavior or stress strain can be predictable.

But if we want to know that thermal behavior or temperature distribution we need to solve the heat conduction equation this particular domain, here the temperature distribution so output is it is a variable of the temperature in the each node point of a solution domain. And of course a material flow also we can able to predict.

We can model in the material flow during this machining process basically chip flow. But in this case the two approaches solid mechanics and the fluid mechanics based approach. So solid mechanics with both the cases the it can be represented this in the (39:34). But of course if you follow the fluid mechanics approach we need to know solve the Stokes equation or you can say Navier-Stokes equation such that it can predict the velocity field at this node point.

But of course in this cases the material behavior can be as the viscoplastic material and then we can predict this approach this standard. Solid mechanics approach we need to know constitutive relation different plasticity model we need to adopt and we can predict that deformation or distortion behavior each and every node or we can say the displacement each and every node and from the displacement we can estimate the strain.

And of course strain rate estimation can also be possible that in case of the solid mechanics approach.

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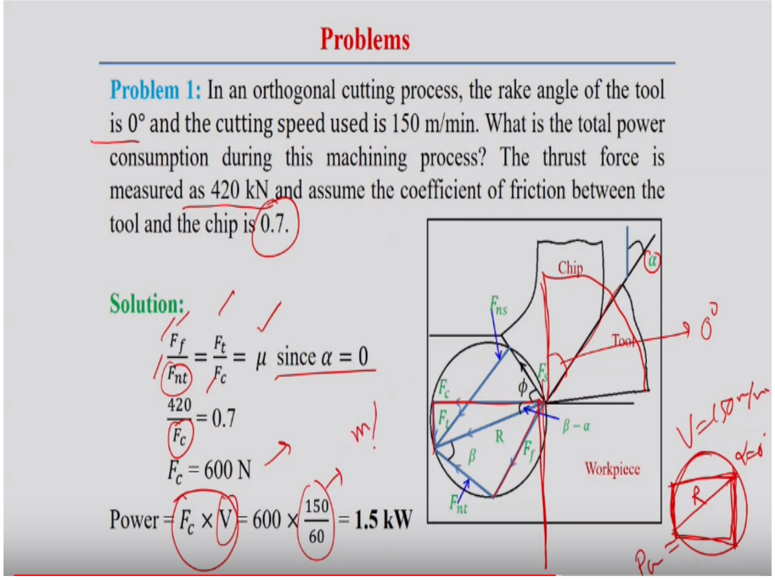

Problems

Problem 1: In an orthogonal cutting process, the rake angle of the tool is 0° and the cutting speed used is 150 m/min. What is the total power consumption during this machining process? The thrust force is measured as 420 kN and assume the coefficient of friction between the tool and the chip is 0.7.

Solution:

$$\frac{F_f}{F_{nt}} = \frac{F_t}{F_c} = \mu \text{ since } \alpha = 0$$

$$\frac{420}{F_c} = 0.7$$

$$F_c = 600\text{ N}$$

$$\text{Power} = F_c \times V = 600 \times \frac{150}{60} = \mathbf{1.5\ kW}$$

Now this we have discussed the analytical model stress analysis model and of course different modelling approach in case of metal cutting processes but now we look into some simple numerical problems that is specific to the metal cutting process. So first look into this first problem. So if we look the we assume the orthogonal cutting process a rake angle of the tool rake angle is defined 0 degree and of course this alpha rake angle.

So this rake angle here it is 0 degree. So that means the tool rake face is basically perpendicular and cutting speed is used V cutting speed is 150 meter per minute. Now we can estimate what is the total power consumption during this machining process and of course the thrust force is thrust force is given 420 kilonewton.

Basically cutting force is sorry thrust force is given and that Ft so Fc replace to Ft is given, thrust force 1 Ft is given 420 kilonewton and coefficients friction we assume 0.7 between the workpiece material. With this information we need to estimate power consumption during the machining process. So power consumption during the machining process we can estimate that power=cutting velocity in the cutting force this is the cutting force Fc and the cutting velocity.

So cutting velocity, cutting speed or velocity so cutting velocity is defined but we need to estimate what is the Fc. Now since this alpha=0 that means rake angle=0 we can estimate the Ff frictional force and the normal force Fnt so frictional force and Fnt. So it will be like that so frictional force will be acting here. So it is the diagram with resultant force of frictional force will be this because rake angle=zero.

So it is a there is some kind of horizontal line similarly the cutting force will be here and Ff will be this, thrust force will be this. So this is simplified because alpha=0 degree. So this is the resistance Ra, this is the Ra=the resultant force. So it is easily estimate that Ff by this th=Ft/Fc and even if we look into the Merchants circle diagram if we put alpha=0 in that expression we can find out this ratio which is equivalent to the coefficients of the friction.

Since alpha=0 so from here we can easily estimate Fc, Fc=600 kilonewton and estimate the cutting velocity is given meter per minute we need to convert in the this is 150 meter per second so joule per second watt we can estimate and from the watt to we can convert into the kilowatt so it becomes 1.5 kilowatt.

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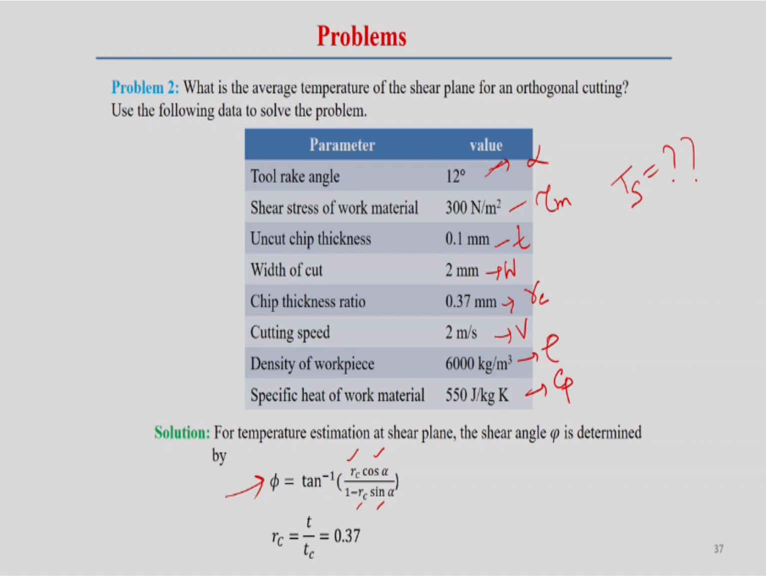

Problems

Problem 2: What is the average temperature of the shear plane for an orthogonal cutting? Use the following data to solve the problem.

Parameter	value	
Tool rake angle	12°	α
Shear stress of work material	300 N/m²	τ_m
Uncut chip thickness	0.1 mm	t
Width of cut	2 mm	W
Chip thickness ratio	0.37 mm	r_c
Cutting speed	2 m/s	V
Density of workpiece	6000 kg/m³	ρ
Specific heat of work material	550 J/kg K	C_p

$T_s = ??$

Solution: For temperature estimation at shear plane, the shear angle φ is determined by

$$\phi = \tan^{-1}\left(\frac{r_c \cos\alpha}{1 - r_c \sin\alpha}\right)$$

$$r_C = \frac{t}{t_c} = 0.37$$

Next problem what is the average temperature of the shear plane for an orthogonal cutting situation so we have the given data. So we need to estimate what is the average temperature of the shear plane. So we need to estimate what is the shear plane temperature Ts, tool rake angle is given, shear stress of the work material which is given Tau m.

And then uncut chip thickness t is given, width of the cut is given W, chip thickness ratio rc is given, cutting speed velocity V is given, density of the workpiece Rho is given and specific heat of the work material the Cp specific work material also given and tool rake angle alpha is also given. So all this parameter are defined now we have to estimate the shear plane temperature. So from here we can find out the temperature estimation of the shear plane.

The shear first we need to know the different angles different information so shear angle is not given here and of course we can estimate the chip thickness ratio is given. But there is a relation that this already we derive that shear angle =tan inverse, chip thickness ratio cos alpha 1 - rc sin alpha. So alpha and rc is defined so from here we can easily rc this thing is 0.37 t/tc is already defined. So from here we can estimate phi shear angle.

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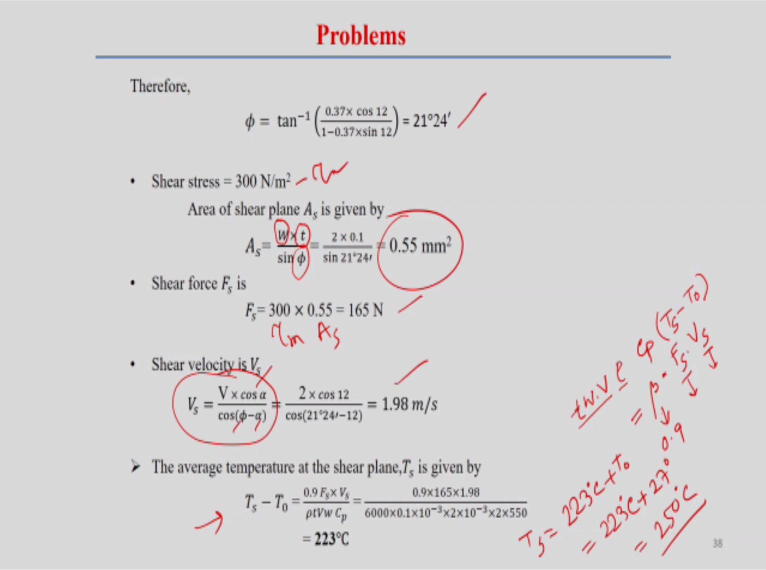

Problems

Therefore,

$$\phi = \tan^{-1}\left(\frac{0.37\times \cos 12}{1-0.37\times\sin 12}\right) = 21°24'$$

- Shear stress = 300 N/m² – τ_m

  Area of shear plane A_s is given by

  $$A_s = \frac{W\times t}{\sin\phi} = \frac{2\times 0.1}{\sin 21°24'} = 0.55\ \text{mm}^2$$

- Shear force F_s is

  $$F_s = 300 \times 0.55 = 165\ \text{N}$$

  $\tau_m A_s$

- Shear velocity is V_s

  $$V_s = \frac{V\times\cos\alpha}{\cos(\phi-\alpha)} = \frac{2\times\cos 12}{\cos(21°24'-12)} = 1.98\ m/s$$

➢ The average temperature at the shear plane, T_s is given by

$$T_s - T_0 = \frac{0.9\,F_s\times V_s}{\rho t V w\, C_p} = \frac{0.9\times165\times1.98}{6000\times0.1\times10^{-3}\times2\times10^{-3}\times2\times550}$$

$$= 223°C$$

$t w V \rho\, C_p (T_s - T_0) = 0.9\, F_s V_s / J$

$T_s = 223°C + T_0$

$= 223°C + 27°$

$= 250°C$

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So shear angle put all these values it is the 21 degree. So it is given shear stress also given 300 Newton per meter square. Now area of the shear plane we can easily estimate width of the cart is given and t we can estimate because I think t is given here so from here we can estimate the t sin phi or I will estimate the shear area easily find out. Then shear force, shear force can be estimated the shear stress and shear area that is the shear force.

So one was to estimate the shear force then shear velocity Vs so Vs from velocity triangle we can estimate the Vs in terms of the V cos alpha cos phi - alpha so V is given, alpha is defined phi alpha. All are defined so from here we can estimate what is the shear velocity. So once you know the shear velocity then we can look into this the material removal rate that means uncut chip thickness, width of the chip and the cutting velocity that increase the material removal volume flow rate.

We multiply by density, this is the mass flow rate and material removal rate. Then we can equivalent to m mass flow rate, then the Cp and delta T temperature rise so these are the temperature final temperature that is the initial temperature which =assume the beta percentage of the heat is converted to the shear in the shear energy and remaining may be loss then th=the shear energy.

That is force*velocity shear force * shear velocity is the energy=so beta is we assume that 0.9 so assume the or may be defined 90% it is energy shear energy converted to the heat energy so 0.9 and shear force we have already estimated shear velocity we have already estimated, we put all this value then from here we can estimate Ts-T0=this a parameter is known.

And from here Ts=whatever this value=223 degree centigrade + T0. See if we define 223 degree centigrade the T0 is assumed that initial temperature, ambient temperature=27 degree then it becomes 250 degree centigrade. So this is the roughly estimation of the shear plane average temperature at the shear plane during the shear deformation of a machining process.

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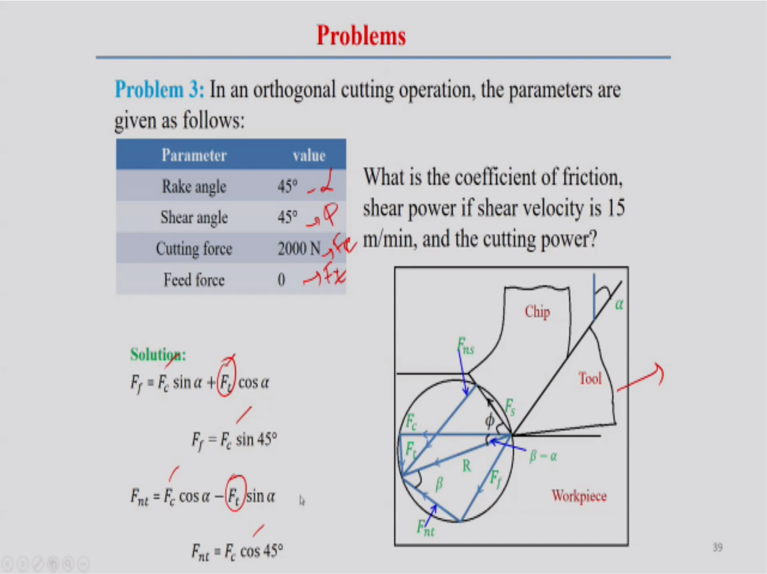

Problems

Problem 3: In an orthogonal cutting operation, the parameters are given as follows:

Parameter	value
Rake angle	45° → α
Shear angle	45° → ϕ
Cutting force	2000 N → F_c
Feed force	0 → F_t

What is the coefficient of friction, shear power if shear velocity is 15 m/min, and the cutting power?

Solution:

$$F_f = F_c \sin\alpha + F_t \cos\alpha$$

$$F_f = F_c \sin 45^\circ$$

$$F_{nt} = F_c \cos\alpha - F_t \sin\alpha$$

$$F_{nt} = F_c \cos 45^\circ$$

39

If we look into an another problem the orthogonal cutting operation, the parameters are given here. Rake angle is given, shear angle also given define, cutting force Fc is given but Ft=0, feed force=0 that means Ft=0. Now we have to estimate what is the coefficients of the friction, shear power if shear velocity is 15 meter per minute and the cutting power, 3 different power we need to find out.

So of course so we need to know the Merchants circle diagram from here this is the reference from here we can estimate what is the friction force Ff in terms of the cutting forces Fc, Ft, Fc sin alpha + Ft cos alpha that we can easily find out from the Merchants circle diagram but Ft=0 here so Ff=Fc sine alpha so alpha is rake angle is given so Fc sin 45.

Similarly, in the Fnt that is a normal force during the friction normal force to the friction force that from here Ft=0 and Fc that is alpha=45 degrees so Fc cos 45 degree. So here we can Ff and Fnt both frictional force this friction force and normal force we can estimate in terms of the cutting force.

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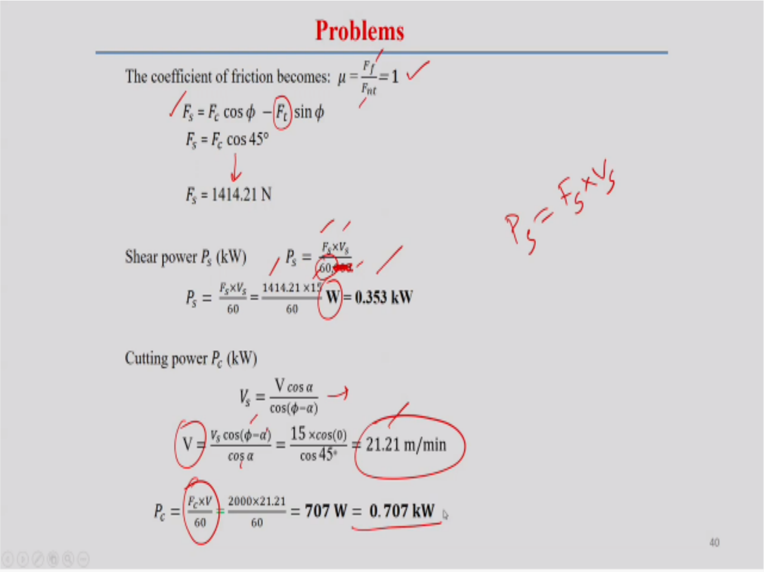

Problems

The coefficient of friction becomes: $\mu = \frac{F_f}{F_{nt}} = 1$ ✓

$F_s = F_c \cos\phi - F_t \sin\phi$

$F_s = F_c \cos 45°$

$F_s = 1414.21\ \text{N}$

$P_s = F_s \times V_s$

Shear power P_s (kW) $P_s = \frac{F_s \times V_s}{60}$

$P_s = \frac{F_s \times V_s}{60} = \frac{1414.21 \times 15}{60}\ \text{W} = 0.353\ \text{kW}$

Cutting power P_c (kW)

$V_s = \frac{V \cos\alpha}{\cos(\phi - \alpha)}$

$V = \frac{V_s \cos(\phi - \alpha)}{\cos\alpha} = \frac{15 \times \cos(0)}{\cos 45°} = 21.21\ \text{m/min}$

$P_c = \frac{F_c \times V}{60} = \frac{2000 \times 21.21}{60} = 707\ \text{W} = 0.707\ \text{kW}$

And coefficient of the friction is the tan beta which is equivalent to the ratio of the this friction Ff/Fnt which is if you see the value put all these two values. I think Ff/Fnt =1 so from f this =1 that means coefficient friction=1 here. Now Fs shear force can also be estimated if ft=0, Fc cos phi, Fc cos 45 degree then we put it this is the shear force in terms of the cutting force.

So shear power in Fs, Fs x Vs x 60,000 but this shear power we can I think we can cut it Fs Ps/60 it depends on the what are the units are given in case of shear force on this thing. So FsxVs actually shear power=FsxVs but whether we divide by 60 or 60,000 it depends what unit want to directly convert or what units are given here. Because Vs actually given in meter per minute.

So it can be convert in terms of the second and that is why divided by 60 is given here. Now we put this value Fs and Vs also 15/60 that is per unit second and that is in terms of watt. Again we divide by 1000 then it becomes in terms of the kilowatt. Similarly cutting power can also be estimated but cutting if we want to estimate the cutting power do we need to find out cutting velocity. So from the velocity triangle a relation between the Vs and V we can relate it.

And from there we can find out what is the cutting velocity V and because phi alpha all are given here then we can estimate the V=this. So here so this is the cutting velocity so once we know this cutting velocity and we can estimate the similar in the cutting power cutting force into velocity and we can find out in terms of kilowatt watt depending what units we are looking for.

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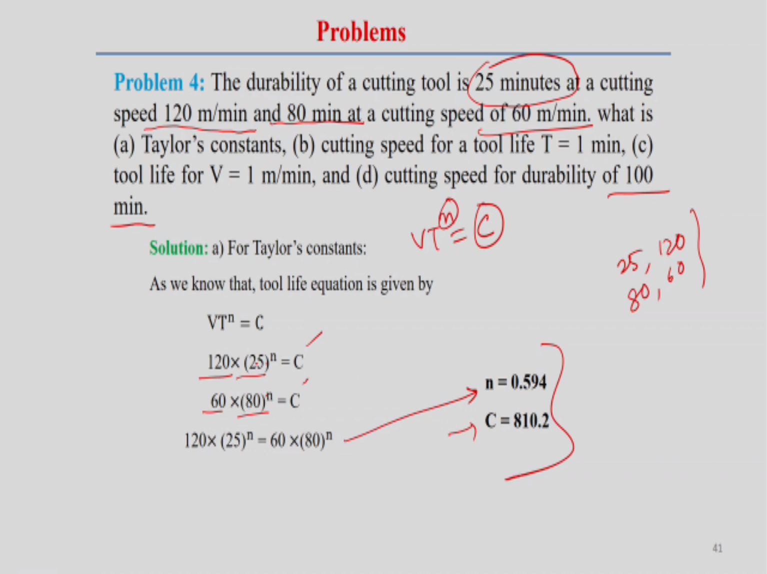

Problems

Problem 4: The durability of a cutting tool is 25 minutes at a cutting speed 120 m/min and 80 min at a cutting speed of 60 m/min. what is (a) Taylor's constants, (b) cutting speed for a tool life T = 1 min, (c) tool life for V = 1 m/min, and (d) cutting speed for durability of 100 min.

$VT^{n} = C$

25, 120
80, 60

Solution: a) For Taylor's constants:

As we know that, tool life equation is given by

$$VT^{n} = C$$

$$120 \times (25)^{n} = C$$

$$60 \times (80)^{n} = C$$

$$120 \times (25)^{n} = 60 \times (80)^{n}$$

n = 0.594

C = 810.2

Now we look into different types of the problem that is the problem for the durability of a cutting tool is 25 minutes. So basically life then is the 25 minutes if we use this cutting tool at a cutting velocity cutting speed 120 meter per minute and the life of the tool may be 80 minute if the cutting speed we use little bit lower at the 60 meter per minute. So these two information are there and the two different conditions that life at two different velocity what is the life what are the life of the tool are given.

Now we have to estimate what is the Taylors constants, what is the cutting speed for a tool life T=1 minute and tool life for V=1 minute and different cutting speed for durability of 100 minute that means what should be the cutting speed we should be use. If the we want to get the life of the tool=100 minute. So we have simply use the Taylors tool life equation because **a** velocity is given that information is given here.

But once it defines velocity, Taylors tool life equation VT to the power n=C, these two things are actually the n and C is the unknown in this particular. But we have some measured data 25 minutes and particular speed is 120. Similarly, 80 minutes and particular speed is 60 meter per minute. So here if we see the Taylors tool life equation, the value of the, the time is given actually minute and the velocity is given meter per minute.

So from here those two equation you can put VT to the power n=C, VT to the power n=C. So from here if we see the 120 the if we make this two equal and then from here we can estimate the what is the value of n. We can take the logarithm in the both side and we can easily find out n. So n=0.594 is the estimate similarly once we know the n we put any of the equation value of the n we can find out the value of C to this.

So this is the first step of Taylors tool life equation, what is the value of the n and C from the other information. So once we decide the value of n and C, then second part is the cutting speed for tool life=1 minute.

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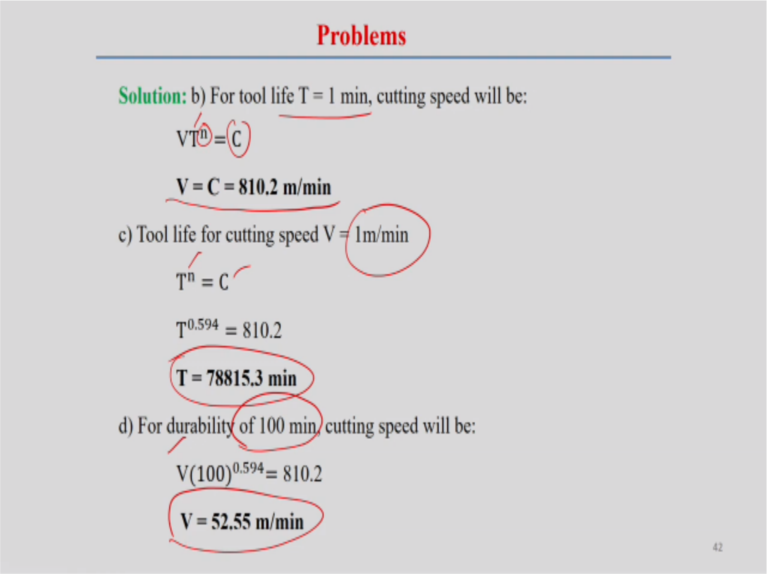

Problems

Solution: b) For tool life T = 1 min, cutting speed will be:

$VT^n = C$

V = C = 810.2 m/min

c) Tool life for cutting speed V = 1m/min

$T^n = C$

$T^{0.594} = 810.2$

T = 78815.3 min

d) For durability of 100 min, cutting speed will be:

$V(100)^{0.594} = 810.2$

V = 52.55 m/min

So for tool life T=1 minute, the cutting speed T=1 we can easily put n is known, C is known. So from here V=C=820 minutes. Similarly, what will be the tool life if cutting velocity is 1 meter per minute. So if we look into that cutting velocity 1 meter per minute if we put all this value we can find out the T=this one. So that means if we use the very low cutting velocity, the life of the tool becomes very high.

Now if we want to predict that if we want the 100 minute then what cutting velocity we should be use for this particular tool. So similarly so V is unknown here put other parameters so V=this thing. So that kind of information from tool, Taylors tool life if we want to get particular life of the tool then what speed we should use, cutting speed we should use for this particular shear.

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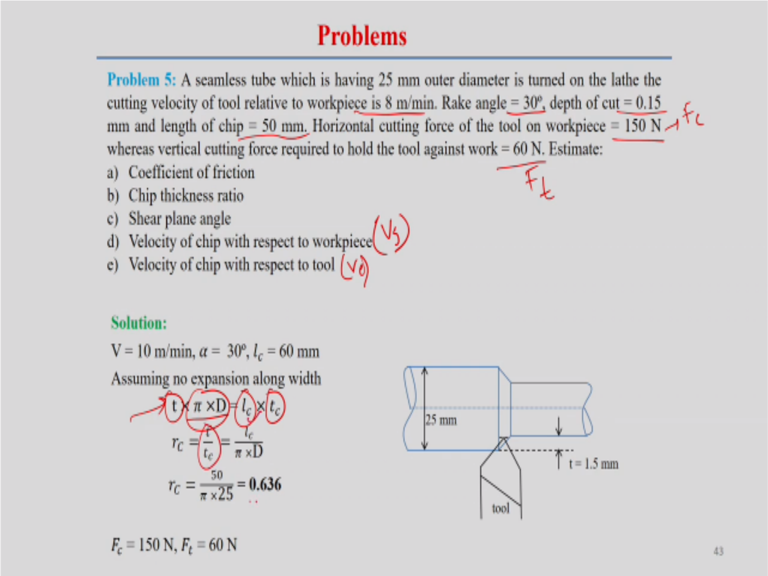

Problems

Problem 5: A seamless tube which is having 25 mm outer diameter is turned on the lathe the cutting velocity of tool relative to workpiece is 8 m/min. Rake angle = 30º, depth of cut = 0.15 mm and length of chip = 50 mm. Horizontal cutting force of the tool on workpiece = 150 N whereas vertical cutting force required to hold the tool against work = 60 N. Estimate:

a) Coefficient of friction
b) Chip thickness ratio
c) Shear plane angle
d) Velocity of chip with respect to workpiece (V_s)
e) Velocity of chip with respect to tool (V_0)

f_c

F_t

Solution:

V = 10 m/min, α = 30º, l_c = 60 mm

Assuming no expansion along width

$$t \times \pi \times D = l_c \times t_c$$

$$r_C = \frac{t}{t_c} = \frac{l_c}{\pi \times D}$$

$$r_C = \frac{50}{\pi \times 25} = \mathbf{0.636}$$

F_c = 150 N, F_t = 60 N

Now another problem would really the seamless tube which is having 25 millimetre outer diameter is turned on the lathe machine cutting velocity is relative to the workpiece is given. Rake angle is defined, depth of cut is defined, length of the chip is defined, horizontal cutting force basically it is we can say this Fc and the vertical cutting force is given also Ft then we need to estimate the coefficient of the friction chip thickness ratio, shear plane angle, velocity of the chip with respect to the tool.

So workpiece and the velocity of the chip this is Vc and this is basically Vs we need to find out. So all information are given. So first step will be the assuming no expansion along though so after chip formation before uncut after cutting there is no expansion along the width direction. Basically width are the same then we can enter the volume flow rate before cutting after cutting make it equal.

We can find out that uncut chip thickness t and one revolution that its total length=length of the chip=pi D. So similarly before cutting so pi D is the length of the chip. So that pi D is travel in the one feed rate so that is that we can say the t x pi D which is lc and tc, the chip thickness. From here we can estimate the chip thickness ratio t/tc and lc/pi D because all information are given here and from here cutting force Fc and Ft two cutting force components are also defined.

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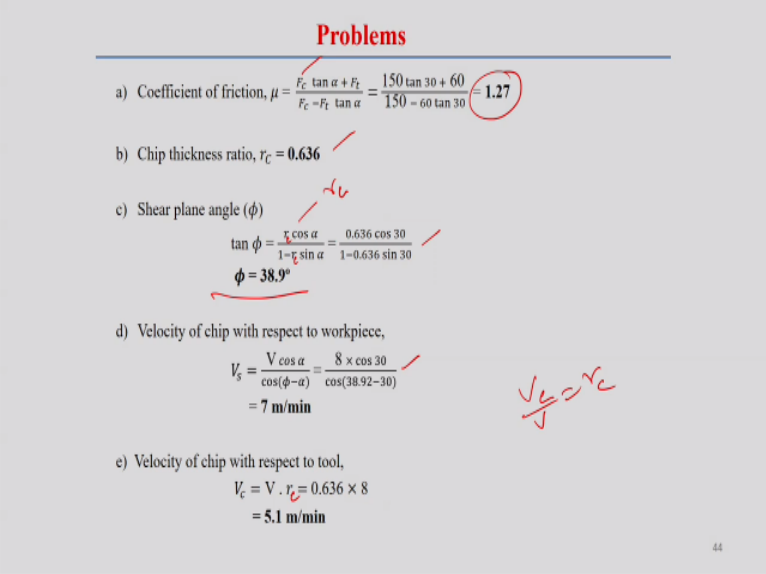

Problems

a) Coefficient of friction, $\mu = \frac{F_c \tan\alpha + F_t}{F_c - F_t \tan\alpha} = \frac{150 \tan 30 + 60}{150 - 60 \tan 30} = \boxed{1.27}$

b) Chip thickness ratio, $r_C = \mathbf{0.636}$

c) Shear plane angle (ϕ)

r_c

$$\tan\phi = \frac{r_c \cos\alpha}{1 - r_c \sin\alpha} = \frac{0.636 \cos 30}{1 - 0.636 \sin 30}$$

$$\underline{\phi = 38.9^\circ}$$

d) Velocity of chip with respect to workpiece,

$$V_s = \frac{V \cos\alpha}{\cos(\phi - \alpha)} = \frac{8 \times \cos 30}{\cos(38.92 - 30)}$$

$$= 7 \text{ m/min}$$

$\frac{V_c}{V} = r_c$

e) Velocity of chip with respect to tool,

$$V_c = V \cdot r_c = 0.636 \times 8$$

$$= 5.1 \text{ m/min}$$

And coefficient of the friction we put this from Merchants circle diagram we estimate 1.27. All these values are given, chip thickness already estimated. Shear plane angle in terms of tan phi=chip thickness ratio basically this r should be rc here. From here we can estimate the value of shear angle. Then velocity of the chip also we can estimate all this information from here the V cos alpha will define the cos alpha phi alpha define.

And velocity of the chip, chip velocity with respect to tool because we already shown Vc/V=rc this should be rc, chip thickness ratio. So we can estimate the velocity of the chip velocity here. So if we look into the overall this kind of problem, first we need to define in first step will be whatever we can estimate the chip thickness ratio normally and shear angle, rake angle is the true geometric property.

So if we estimate all these things and we can find out the different correlation and we can try to solve the this kind of numerical problem.

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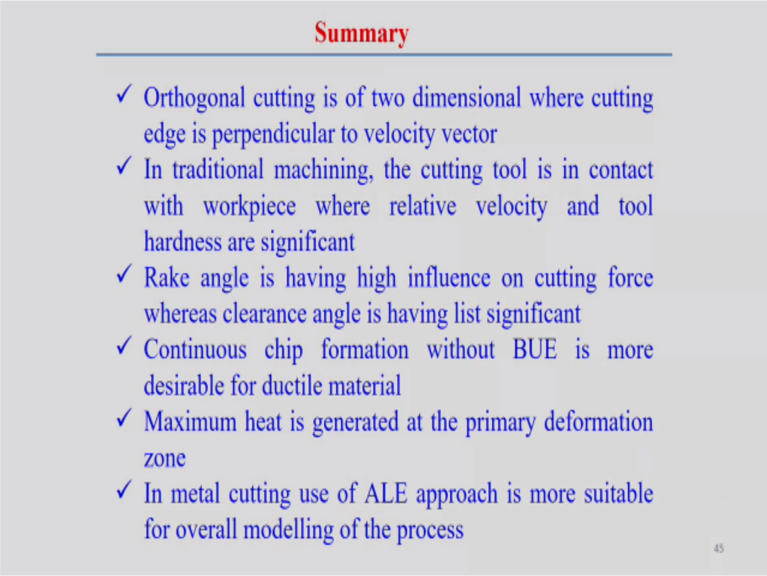

Summary

- ✓ Orthogonal cutting is of two dimensional where cutting edge is perpendicular to velocity vector
- ✓ In traditional machining, the cutting tool is in contact with workpiece where relative velocity and tool hardness are significant
- ✓ Rake angle is having high influence on cutting force whereas clearance angle is having list significant
- ✓ Continuous chip formation without BUE is more desirable for ductile material
- ✓ Maximum heat is generated at the primary deformation zone
- ✓ In metal cutting use of ALE approach is more suitable for overall modelling of the process

So in summary, we can say that it is a conventional machining process, the orthogonal cutting is basically two dimensional process or I define the orthogonal cutting, the cutting is perpendicular to the velocity vector. Second point is that traditional machining, cutting tool is actually in traditional machining or conventional machining process, the cutting tool is actually contact with the workpiece.

Where there is a necessary to bring some kind of the relative velocity between the tool and the workpiece. But in non-conventional machining process and workpiece and at the same time the conventional machining process, the hardness of the tool is more important as compared to the workpiece material and but in non-conventional machining process is not mandatory. The hardness is not important parameter here to perform the non-conventional machining process.

So rake angle is having the high influence on the cutting forces if we look into the two cases the rake angle, shear angle and the friction angle all correlation but nowhere in orthogonal cutting situation there is no role of actually the clearance angle. So practically in mathematically there is clearance angle is less influential parameter in this machining process.

So continuous chip without any built up edge is the most desirable for the ductile material but for brittle material we can expect the discontinuous kind of chip. And of course maximum heat is generated at the primary deformation basically shear deformation zone. And if we look into the modelling approach though ALE approach, arbitrary, Lagrangian, Eulerian approach is more suitable in the machining process.

Specifically, into the machining process where we can take the advantage of the both Eulerian approach as well as the Lagrangian approach. So thank you very much for your kind attention.