Friction and Wear of Materials: Principles and Case Studies

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Lecture – 4
Contact Temperature

In last few lectures of this NPTEL course on tribology of materials, I have discussed the fundamentals of tribology, the friction mechanisms as well as surface characteristics and how to quantitatively characterize tribological surfaces. So, what I am going to do in this particular lecture is to discuss how to quantitatively compute the contact temperature?

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Contact temperature means the temperature rise at the tribological surfaces. And that is largely due to the friction at the mating surfaces. These I think I have mentioned once or twice in last couple of lectures. Precise measurement of the contact temperature at the asperity-asperity contact is next to impossible experimentally. Therefore, it is important to use certain theoretical models to predict that what would be rise in the contact temperature at the asperity-asperity contact surface. Let us first recap.

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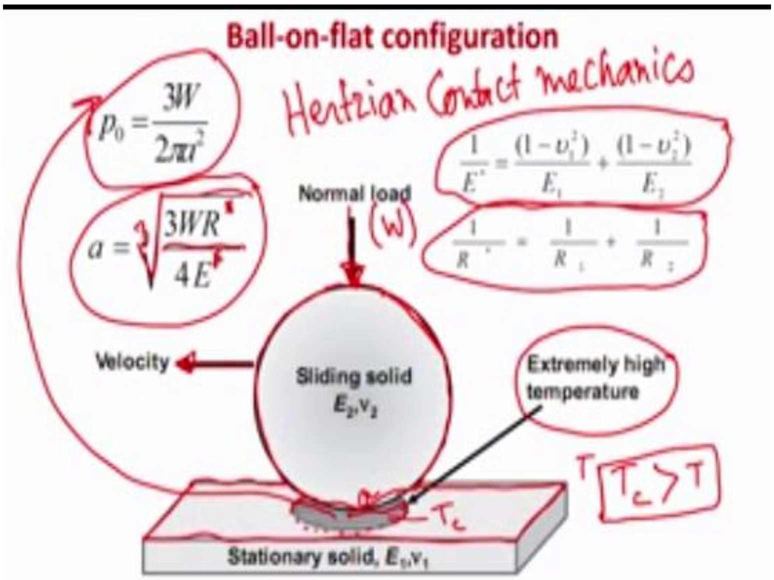

In this particular slide, what would have learned from last 1 or 2 lectures. If you look at this diagram, this is a spherical ball which is in contact with a flat surface. Both these surfaces as you can see, they are nominally flat. If you see this particular flat surface, this flat surface is also nominally flat. However, as I have mentioned couple of times during the course of last 3 lectures, that each of the surfaces whether it is sphere or flat surfaces, they have number of asperities.

These asperities, they have different heights and also, they have different radius of curvature.

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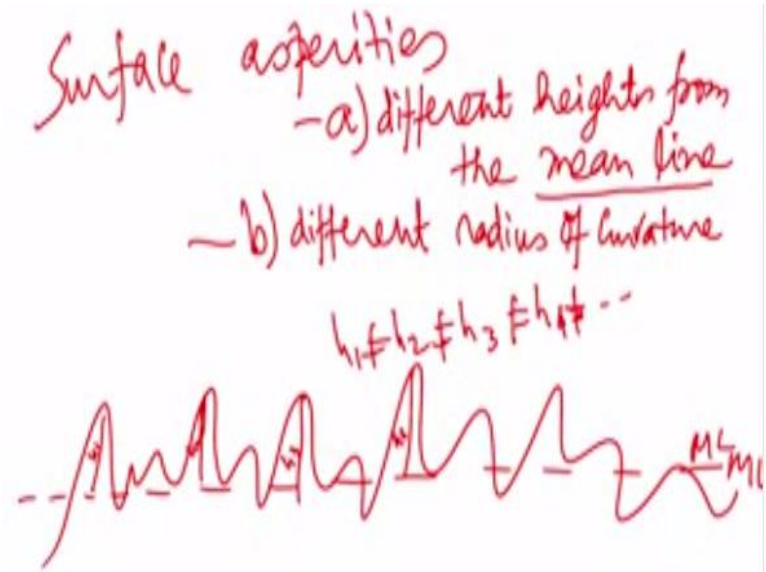

If I recap that surface asperities, surface asperities have 2 different features. Particularly we have mentioned that a. they have different heights from the mean line. So, how to define mean line? Mean line on any particular surfaces, for example, if I refer to this kind of surfaces, this is ML. Mean line is defined as a line which divides the inter surfaces with the fact that above the mean line 50 percent of the material is contained within the asperities and below the mean line again 50 percent of the materials are contained in these asperities.

So essentially what I am saying this is h_1, this height is h_2, this height is h_3, this height is h_4. So $h_1 \neq h_2 \neq h_3 \neq h4$ and so on. So, what I am saying that all the asperities, they have unique heights and second thing these asperities also have a different radius of curvature. So, these are very important things. And this different radius of curvature essentially also would influence the stress behavior, the stress that is experienced at the tribological surfaces.

So, in reference to the earlier discussion and in particular in the context of this particular figure, it has been mentioned that there is a contact zone that will be developed and this is the contact zone. This particular sliding solid, here is the sphere, this will slide against a stationary solid. Then at this contact zone this will experience extremely high temperature. Suppose outside temperature is T and this contact zone average temperature is T_c. So, certainly T_c is greater than T.

What it means is that although you conduct the experiments at ambient temperature, but at the contact zone, temperature is fairly high much higher than the ambient temperature. What is responsible for the increased temperature? The main factor which causes this frictional temperature rise is the coefficient of friction. We will come to that slowly one by one. Now let us recap also what we have mentioned in the last class.

So, this particular sphere is pressed against the flat solid by a normal load W at a given velocity, then what is the average pressure in this particular contact zone?

$$P_o = \frac{3W}{2\pi a^2}$$

where, a is your contact radius.

So, this contact radius can be calculated by this particular equation and if you remember correctly this particular expression comes as solution for the Hertzian contact mechanics.

$$a = \sqrt[3]{\frac{3WR^*}{4E^*}}$$

where

R^* is the effective radius that can be calculated by this one this particular equation,

E^* is the effective modulus that can be particularly expressed by this particular one,

$1/E^*$ is equal to this one.

Now what I am trying to emphasize once more that this contact region not only would experience high contact stresses, but also it would experience extremely high temperature.

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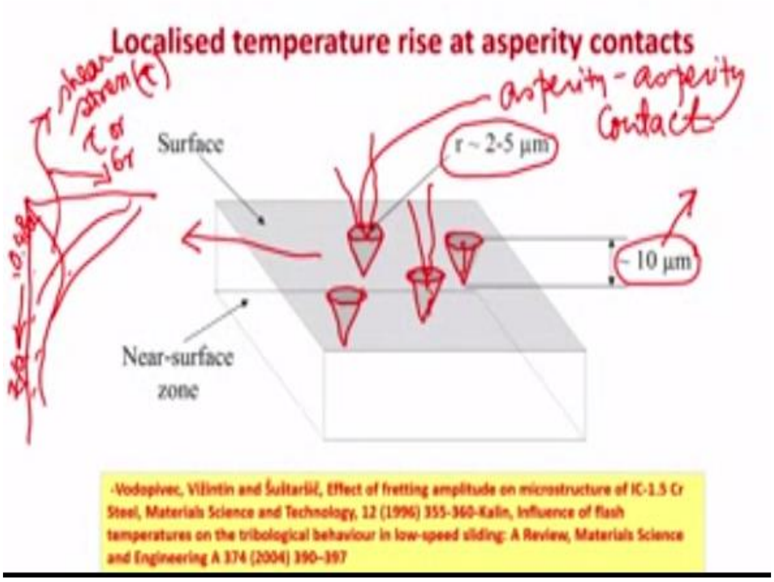

Now, let us look at this contact region little bit more closely. For your better understanding, I am showing here only one surface, the top surface has been removed. So, what you see here in this bottom flat surface that is the conical region here and you can see that this particular conical region is actually what we can call is like a hotspot. This hotspot essentially means the asperity-asperity contact region. So, this is called asperity-asperity contact. So, exactly asperity-asperity contact and they will constitute all these hotspots and will constitute real contact area.

So, if you visualize the situation, what you see that this particular asperity? From the mating solid another asperity comes and that makes this particular contact. But for the simplicity in the representation, here I am not showing the asperity from the top surfaces. I am just showing the bottom surface only. Now let us look at that what is the length scale of this asperity-asperity contact region?

What you see here that radius of this particular contact region is r = 2 to 5 microns. The depth to which this asperity goes below in the surface is 10 microns. So, essentially what you need to remember that typical contact region radius is 2 to 5 microns and this depth is also going to 10 microns. This depth is a region where any heat that is generated, it will be conducted through the solid. So, essentially although the tribology friction and wearing surface dominated phenomena, but if you remember in the last lecture, I have mentioned that there is something called subsurface stress region.

So subsurface stress region means, if I draw here corresponding subsurface stress region, there is a shear stress which goes to a maximum and this maximum is 0.48 times a. a is your contact radius. So, this is your dimension z/a. a is your contact dimension and this is your stress either τ or σ_r and there are some of the stress which will go like this, some of the stress profile will go like this. So, this is your shear stress τ. And then you can see that how this stress will.

So, what I am saying that all these stress distribution and temperature both will vary in this 10-micron depth. So, this 10-micron depth is quite large and across this length scale in the z directions, the stress and temperature will vary.

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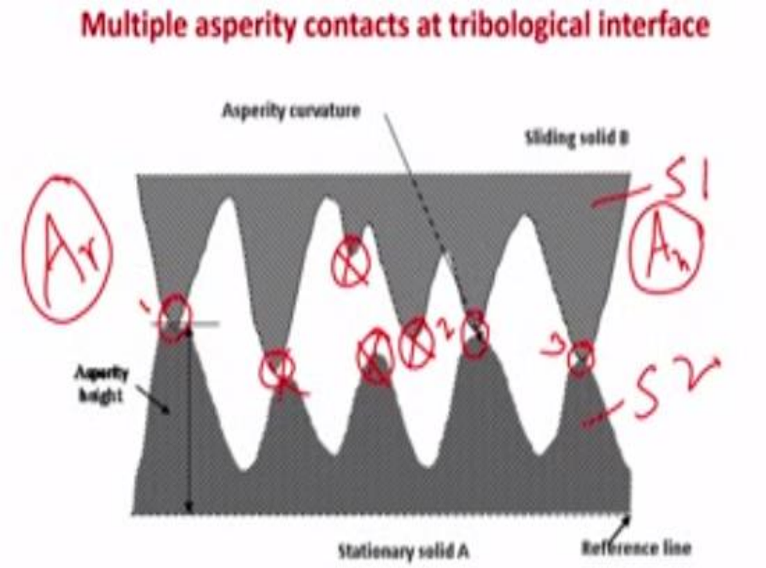

Now this one is again showing that multiple asperity-asperity contact. Suppose if it is your solid 1 and this is your solid 2, so this is one particular area asperity-asperity contacts, this is another one, this is third one. So, what you see that although your nominal contact area would constitute all the asperity-asperity surfaces, but your real contact area. You have something called nominal contact area of the surface and you have something called real contact area of the surface. So, real contact area would essentially constitute of 1+2+3.

I hope I am clear on this particular point. So, real contact area essentially would constitute of the actual asperity-asperity contacts. It will not constitute of this one, no; it will not constitute this one, no; it will not consider this one; it will not consider this one. Wherever the asperities from both the solids, they come and they interact, that is the region that will constitute the real contact area A_r.

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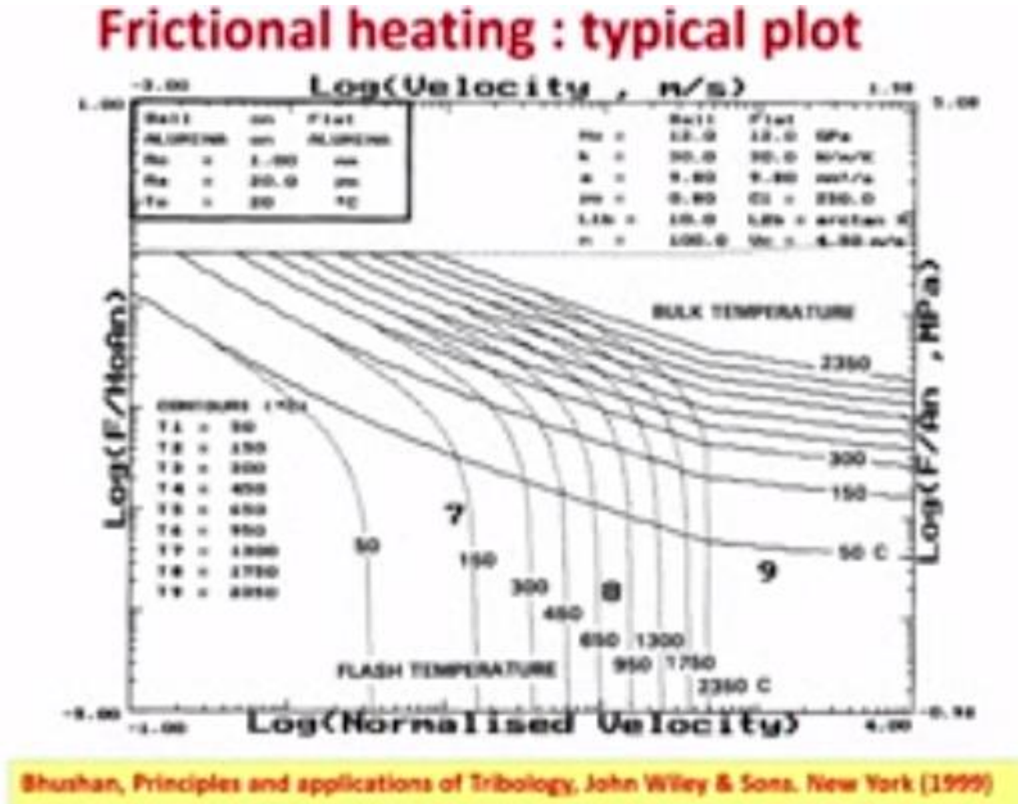

Now we will see some of these equations.

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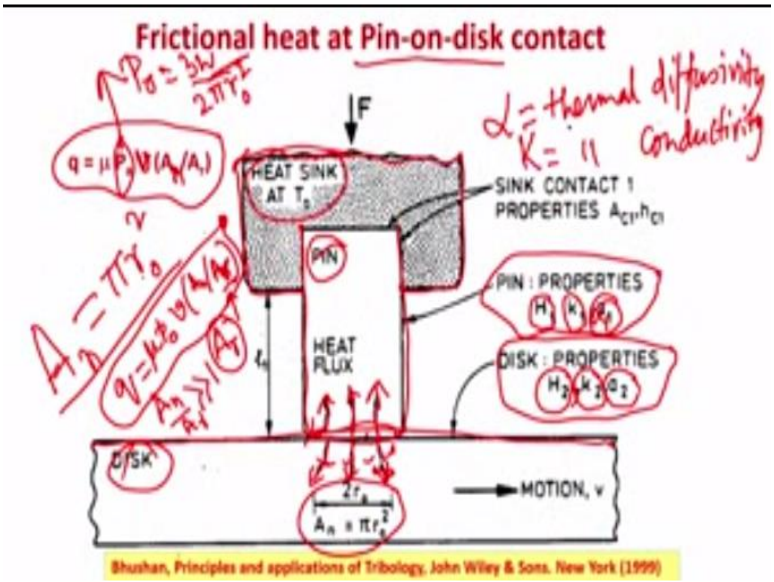

So, this is with reference to pin-on-disk. why pin-on-disk? Because pin-on-disk contact is most widely used in tribological research and also tribological industry. So, pin-on-disk is kind of widely accepted. Pin, it is a cylindrical pin. The cylindrical pin is held in a particular pin holder and this pin holder is what is like a heat sink. So, it is kept at an ambient temperature T_o. Now this is a pin and this is your contact area right. So, this contact area is essentially what we are saying that nominal contact area.

Nominal contact area, I have mentioned to you in the last slide. So, nominal contact area

$$A_n = \pi r_o^2$$

where r_o is your contact radius. Now you have a disk which can be either rotating or your pin can be stationary. So, one of these mating solids either pin or disk is either stationary or rotating. Now this is the contact area A_n, nominal contact area, not real contact area. Where, heat will be generated and then heat flux will be conducted either through pin or through the disk.

In other words, you can say that whatever heat that will be generated at the contact region that will be partitioned between the pin and between the disk. Now to what extent this will be partitioned between the pin-on-the disk? That depends on what are the relative properties of the pin? and what are the relative properties of the disk? So relative properties of the pin, disk properties where K_2 is you for thermal conductivity and α is a thermal diffusivity, similarly pin is that K_1 is the thermal conductivity and α_1 is the thermal diffusivity.

So typically, α is your thermal diffusivity and K_1 is your thermal conductivity. So, the subscript 1 and 2 essentially means that is whether it is a disk or in the pin. Now what would be total heat that would be generated that has been mentioned here. Total heat is nothing but

$$q = \mu P_a v(\frac{A_n}{A_r})$$

μ is coefficient of friction, P_a is nothing but Po if you remember correctly

$$P_o = \frac{3W}{2\pi a^2}$$

So, this is your P_o that is the apparent contact pressure or nominal contact pressure, this v is your sliding velocity, what is A_n? A_n is your nominal contact area and A_r is equal to real contact area.

Your real contact area is this one A_r. **(Video Starts: 16:11)** so, A_r if you look at this particular slide it is very clear to you that A_r would be much less than A_n. Physically it is clear. Real contact area is much smaller than the nominal contact area. Because nominal contact area is across the inter-surface and real contact area will constitute only the asperity-asperity contact. So now if you go back to this particular case, from this particular case A_n/A_r, with this argument A_n/A_r would be much greater than 1 because your A_r is very small.

If A_r is small then A_n/A_r would be much greater than 1. So, you can see from simple arguments that heat generated would be quite substantial in magnitude **(Video Ends: 17:06)**.

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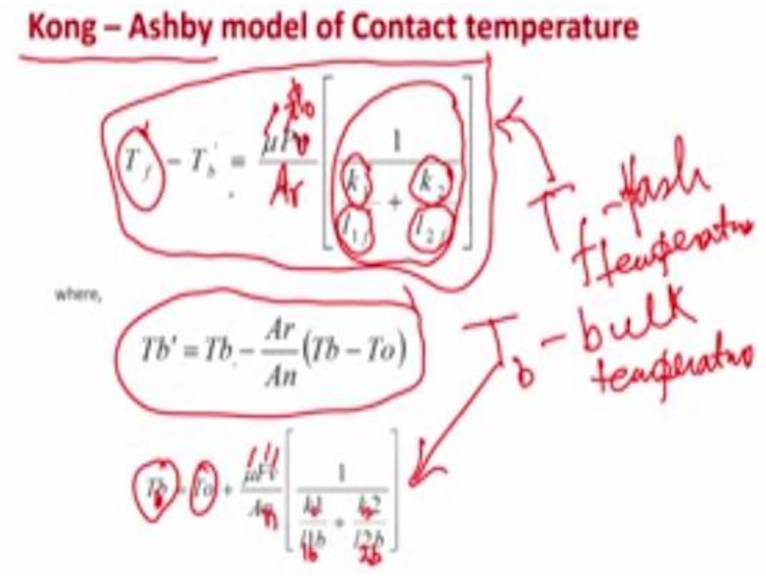

This heat that will be partitioned between the pin and the disk that we can calculate by this particular equation. There are several models that are available. One of the models is called Kong-Ashby model. Mike Ashby was a professor at Cambridge University. What they proposed that flash temperature T_f. what is flash temperature? There are two temperatures that are important.

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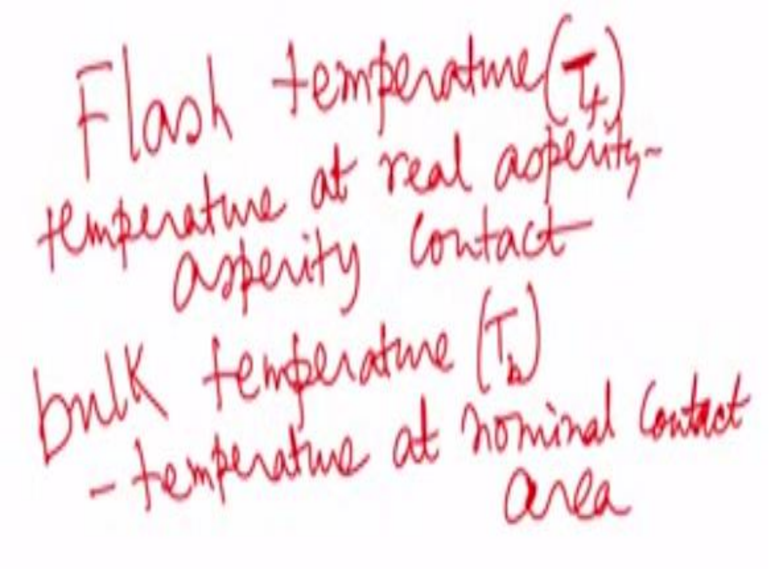

One is called flash temperature. Flash temperature is nothing but the temperature at real asperity-asperity contact and there is something called bulk temperature. In all these mathematical equations that will follow now, we will be using these 2 terms, one is the flash temperature T_f and one is the bulk temperature T_b. This is the temperature at nominal contact area. **(Video Starts: 18:54)** Nominal contact area means that is a contact area which will comprise entire things.

So, this nominal contact area would be A_n. But real contact area would constitute only these three contact points. Particularly in reference to this particular figure **(Video Ends: 19:06)**. if you look at these equations, what you see here that T_f is your flash temperature. Now T_b prime can be found out from this particular equation, μ is your coefficient of friction, P is nothing but P_o, v is your sliding velocity, A_r is your real contact area. So, the moment you put A_r, A_r is much smaller than A_n. Typically your flash temperature would be very high.

Now, there are terms again inside this particular bracket what you see 1 upon K_1 is your thermal conductivity, l_{1a} is your thermal heat distance like you know length scale through which heat is conducted in the pin. K_2 is your thermal conductivity of the disc, and l_{2f} is your thermal diffusivity distance in the disc. So, that means the distance through which heat is conducted in the disc. Now T_b is your bulk temperature as I said before. So T_f is your flash temperature and T_b is your bulk temperature.

Now $T_{b,}$ what you see T_o is your actual ambient temperature, μ F_p/A_n. So, in one of the cases T_f flash temperature you see that is real area of contact is taken A_r. When you define the bulk temperature, it is the nominal contact area A_n which is taken, μ is the coefficient of friction, F is the frictional force, v is your sliding speed, $1/K_1$ and K_2, K_1 is your thermal conductivity of solid 1, K_2 is your thermal conductivity of solid 2, and l_{1b} is your thermal diffusion distance in bulk in solid 1 and bulk in solid 2.

So, if you plug in all these values, now T_b values you put it here and then if you put this T_b prime values here, then you can get the T_f. So bulk temperature calculation is fairly easier compared to flash temperature. So, this T_f and T_b you can calculate in this manner.

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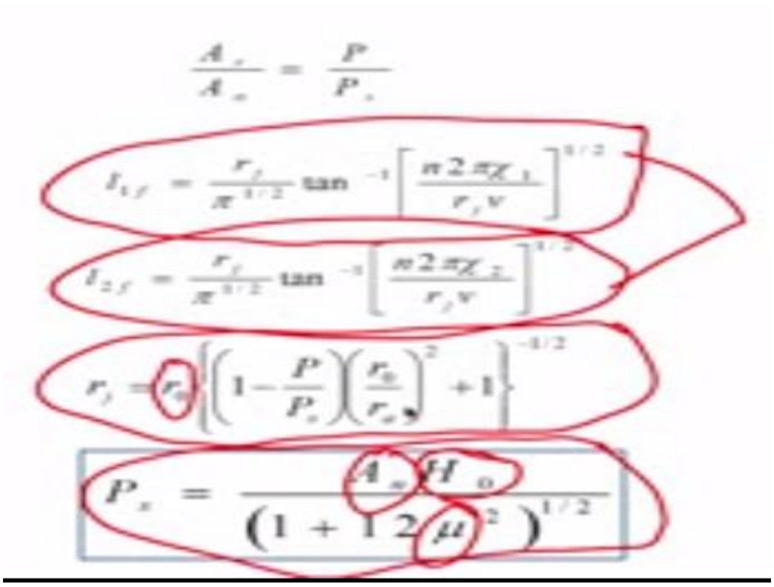

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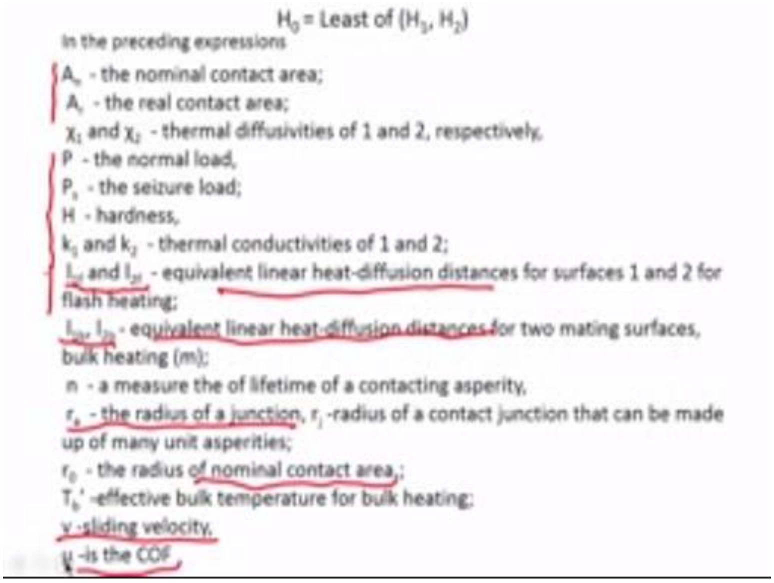

H_0 = Least of (H_1, H_2)

In the preceding expressions

A_n - the nominal contact area;

A_r - the real contact area;

χ_1 and χ_2 - thermal diffusivities of 1 and 2, respectively,

P - the normal load,

P_s - the seizure load;

H - hardness,

k_1 and k_2 - thermal conductivities of 1 and 2;

l_{1f} and l_{2f} - equivalent linear heat-diffusion distances for surfaces 1 and 2 for flash heating;

l_{1b}, l_{2b} - equivalent linear heat-diffusion distances for two mating surfaces, bulk heating (m);

n - a measure the of lifetime of a contacting asperity,

r_a - the radius of a junction, r_j -radius of a contact junction that can be made up of many unit asperities;

r_0 - the radius of nominal contact area,;

T_b' -effective bulk temperature for bulk heating;

v -sliding velocity,

μ -is the COF

Now these other things which are important, this is actually that all these different parameters which are used in all these expressions. A_n and A_r as I said nominal contact area and real contact area, then this is P is your normal load, H is your hardness, k_1 and k_2 is your thermal conductivities of solid 1 and solid 2, l_{1f} and l_{2f} I have mentioned while defining flash temperature that is equivalent linear heat diffusion distance, l_{1b} and l_{2b} is your equivalent linear heat diffusion distances for the two mating solids in case of bulk heating.

And the r_o is your radius of normal contact area, r_a is the radius of a junction, v is your sliding velocity, and μ is your coefficient of friction. So again, how to find out that l_{1f} and l_{2f} **(Video Starts: 23:05)** So if you look back to this particular figure to get a physical significance of this one. so l_{1f} and l_{2f} is this particular case, for example this is your l_{1f} like heat diffusion distance in solid 1 and this is your l_{2f} like heat diffusion distance in solid 2. Now the way I am describing it, it is far more difficult to compute this l_{1f} and l_{2f}.

Based on several geometric consideration and also thermal conditions at the contact-contact junction, this l_{1f} and l_{2f} can be calculated by these two equations and what you see here that is

$$l_{1f} = \frac{r_j}{\pi^{\frac{1}{2}}} \tan^{-1}\left[\frac{n2\pi\chi_1}{r_j v}\right]^{\frac{1}{2}}$$

$$l_{2f} = \frac{r_j}{\pi^{\frac{1}{2}}} \tan^{-1}\left[\frac{n2\pi\chi_2}{r_j v}\right]^{\frac{1}{2}}$$

This tan inverse is coming because of some geometric configuration. Now what is n? n is the number of asperities n is a measure of the lifetime of a contacting asperity. What is the lifetime? That means how much time that this contacting asperity will survive in this particular case?

Now χ_1 and χ_2, if you see that χ_1 and χ_2 it is the thermal diffusivities of 1 and 2. So all these things instead of k_1 and k_2 they have put this term χ_2 and from these you can calculate this and r_j how to find out the values of r_j?

$$r_j = r_o \left\{ \left(1 - \frac{p}{p_s}\right)\left(\frac{r_o}{r_a}\right)^2 + 1 \right\}^{-1/2}$$

r_o is your actual contact radius, P_s is defined as the seizure load. Seizure load means at what load these materials they seizure at the contacting surfaces.

Then finally that P_s that is seizure load one can calculate by this particular equation where

$$P_s = \frac{A_n H_0}{(1 + 12\mu^2)^{\frac{1}{2}}}$$

What is H_o? H_o is again defined as the hardness, least of this H_1 and H_2. So essentially if you go back to this particular slide, so suppose this is H_1 and this is H_2 you have to take the lower hardness in calculating this seizure load and A_n is your nominal contact area, mu is your contact coefficient of friction. **(Video Ends: 25:42)**.

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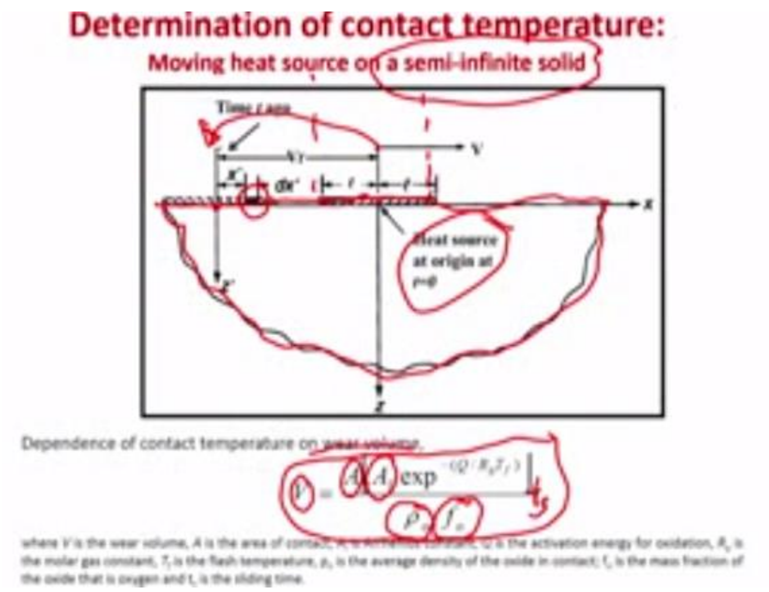

So, then the last point is that for example, how to find out that the contact temperature on a semi-infinite solid? In case of the semi-infinite solid, what will happen? Suppose if you consider that this is your contour of the solid. So, this is the contour of the solid and on which a heat source, what is a heat source? For example, Heat source can be a pin. Because pin is sliding at a distance v at a sliding at a speed v.

Now this heat source at a time t=0 is here. At time t = t, the heat source is placed in sliding in this -x direction and if it goes -X direction, then it goes from this region to this region and then you find out that what is the heat that will be generated. Now why contact temperature is so important? contact temperature is important because, that wear volume V also related to the contact temperature to this particular equation.

For example, what you see here? This has some kind of Arrhenius type of relationship where

$$V = \frac{A[A_l exp^{-\left(\frac{Q}{R_g T_f}\right)}]}{\rho_o f_o}$$

What is R? R is your universal gas constant, T_f is your flash temperature, ρ_o is the average density of the oxides that is formed and f_o is a mass fraction of the oxide that is oxygen. Then all these equations essentially tell that all these parameters are to be multiplied by t_s, t_s is your sliding time. So, what you see here? Very clearly V is the wear volume, a is your area of contact, A_l is your Arrhenius constant.

So, the P exponential time within the bracket is your P exponential time is Arrhenius constant. Your exponential time q is your activation energy for the diffusion or oxidation, r is your universal molar gas constant, and t_f is your flash temperature. So, from here, you can clearly see that flash temperature also can influence to a large extent what is the wear volume.

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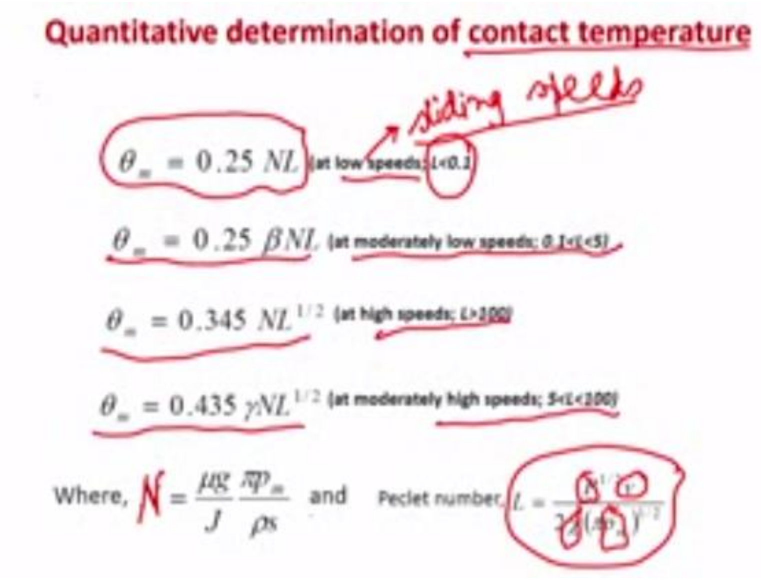

Now one is to also understand that this contact temperatures depending on the sliding speed. So, depending on the sliding speeds different equation needs to be used to find out that what is a contact speed. For example, at low speed L, L is your Peclet number and this Peclet number is defined here. So, if L is less than 0.1, then maximum temperature is equal to 0.5NL.

If it is moderately low speeds 0.1 to 0.5, then θ_m = 0.5 to 0.25 βNL, and again if it is high speeds L greater than 100, then θ_m is proportional to 0.345 NL to the power half, and at very high speed is 5 less than L less than 100, θ_m = 0.435 γNL to the power of half. While L is mentioned here as a platelet number which is $P^{1/2}$, v is your sliding speed, this is your thermal diffusivity, it is your mean contact pressure, and this is your load and what is N?

$$N = \frac{\mu g}{J} \frac{\pi p_m}{\rho s}$$

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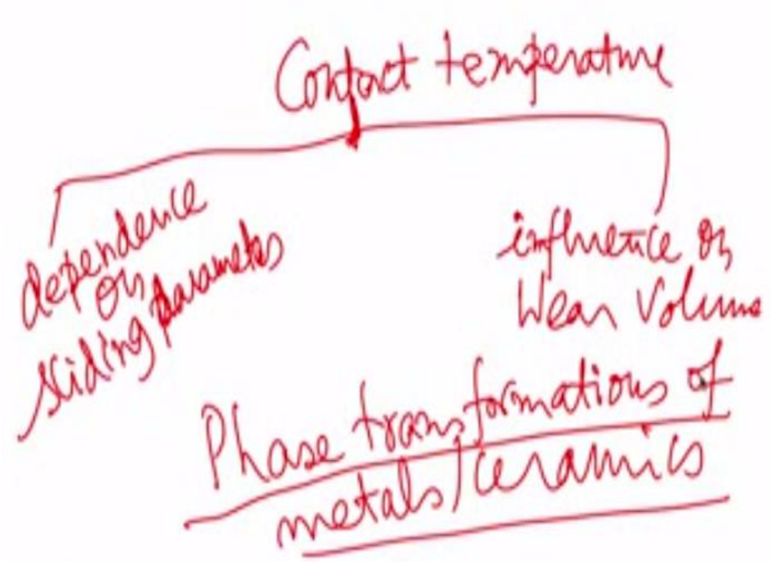

So, overall what you learnt is that how this contact temperature can be determined? So, again this contact temperature is one thing that depends on sliding parameters. So that is very important that how this contact temperature varies on sliding parameters? and how this contact temperature also influences the wear volume? These influence on wear volume you can also find out that flash temperature and then from there how this oxidation takes place? and then how it would influence the wear volume?

In metals for example, phase transformation also takes place. In metals and some of the ceramics like zirconia and all phase transformations of metals and ceramics are largely influenced by contact temperature. So, from material science point of view, the contact temperature is very important because contact temperature can cause certain phase transformation in titanium alloys or some zirconia ceramic to happen, and as a result the material properties also would change substantially because of the large contact temperature. Thank you.