**Friction and Wear of Materials: Principles and Case Studies**
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**Lecture - 12**
**Friction and Wear of Metal Matrix Composites**

Welcome back to the NPTEL course on tribology of materials. We have covered few lectures on the fundamentals of tribology that friction and wear, what are the governing rules, how the friction causes the increase in the contact temperature at the asperity contacts, what is lubrication and how lubrication helps in reducing coefficient of friction, again what is the minimum lubricant film thickness that will give longer life to wearing surfaces.

And the last one that I have covered on the engineering materials where I have mentioned that there are 3 classes of primary materials.

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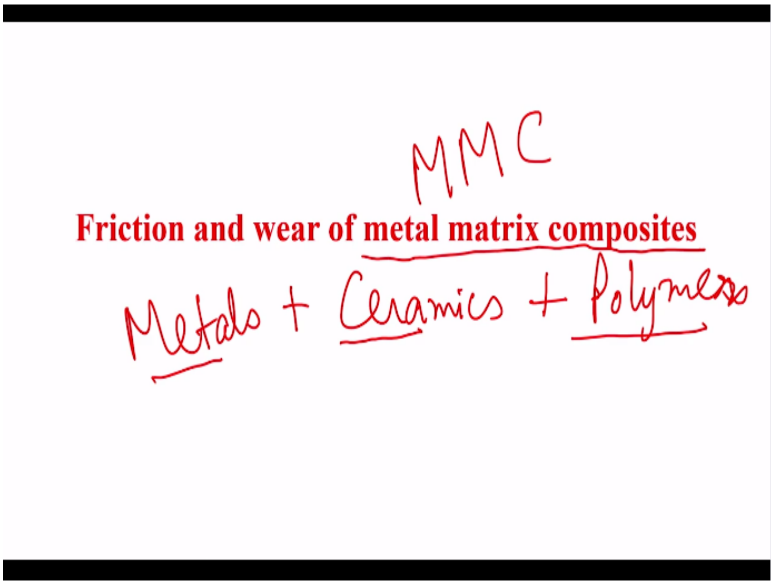


That is metals, then ceramics and then polymers right. I have given also examples that what are the specific properties which are advantageous for tribological applications of these 3 primary material classes. At the same time, I have emphasized that composite is a derived material class which can combine advantageous properties of metals and ceramics or advantageous properties of ceramics and metals or advantageous properties of metals and polymers.

Depending on which constitutes the matrix phase, we designate the composite accordingly. For example, MMC stands for metal matrix composite. So here the metal constitutes the matrix of the composite, ceramic phase are used as dispersed reinforcements in the metallic matrix. In this particular lecture, I will show you one case study from our own research group where we have investigated the friction and wear of metal matrix composites in fretting mode.

What is fretting mode? I will explain to you in few minutes but before that let me also give little bit more introduction on the metal matrix composites.

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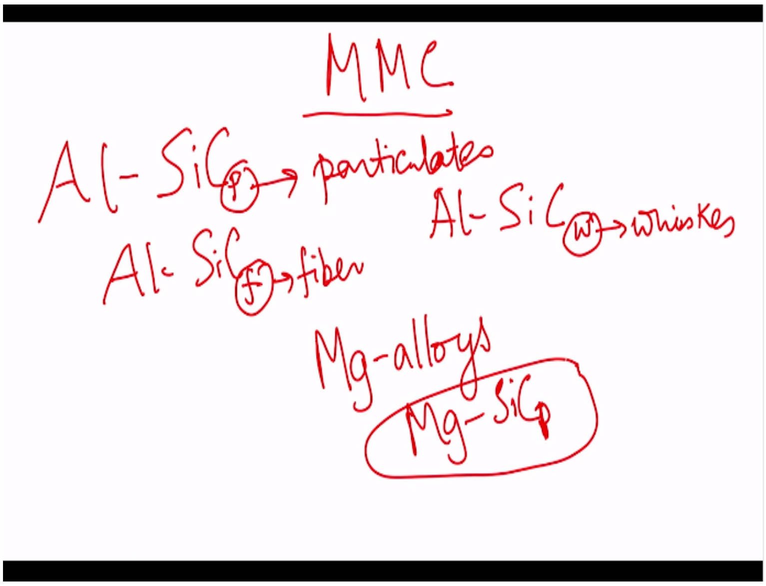


So metal matrix composites one of the popular example in the material science field of the metal matrix composites is aluminium, silicon carbide composites. So I mentioned P as a subscript which means that this is the silicon carbide particle let us imply so why I said because silicon carbide is available not only in particulates but also in viscous so if you use the viscous of silicon carbide viscous as reinforcement we call it as aluminium silicon carbide viscous so w in the subscript essentially stands for viscous.

Then, if you have aluminium silicon carbide fibres then we can call it as aluminium silicon carbide fibres and then if it is used as a metal matrix composites silicon carbide fibres reinforced aluminium matrix. Now aluminium is one of the materials which has attracted lot of attention for (()) (04:10) applications because it is light weight. At the same time, in very recent times magnesium alloys that have also attracted lot of attention.

Because magnesium is light weight even ultra-light weight, even the density of magnesium is less than that of aluminium. So similar to aluminium silicon carbide composites therefore people have developed magnesium silicon carbide composites as well and silicon carbide again is in the particulate form so magnesium silicon carbide particular composites for example is one of the composites that are being developed.

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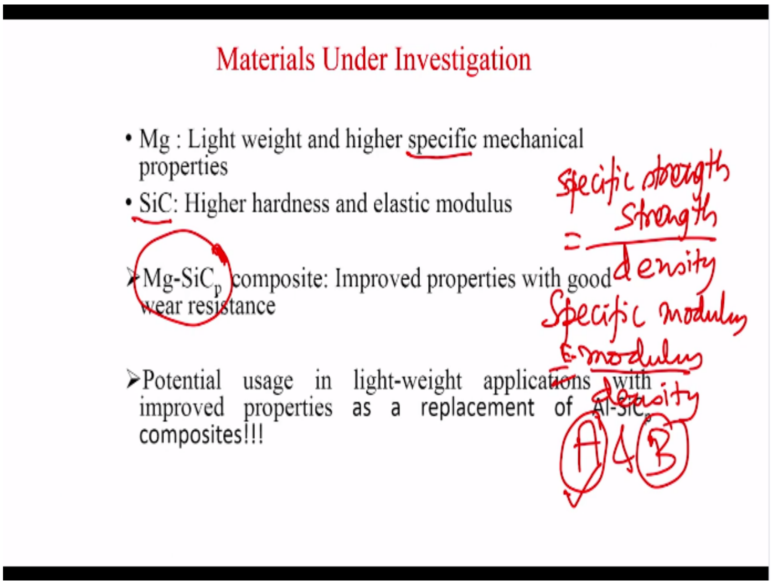


So this magnesium silicon carbide composites is what we have used in this present case study and why magnesium, I have already mentioned it is light weight and therefore it has higher specific mechanical properties. Whenever I use the word specific what it means like for example specific strength essentially means strength/density, specific modulus essentially means modulus/density.

So just to give an example elastic modulus/density, just to give an example if two material A and B has similar elastic modulus and similar strength but A has a lower density than B, then A will have higher specific strength than B. So the specific strength properties where specific mechanical properties are important where weight reduction keeps extra mileage or extra benefits for certain technological applications.

Silicon carbide, why silicon carbide? Silicon carbide is higher hardness and elastic modulus and like any other ceramic materials particular non-oxide ceramics like silicon nitride, titanium diboride and so on like that several other non-oxide ceramics silicon carbide has higher hardness and elastic modulus. So it is therefore quite perceivable that magnesium silicon carbide composite should have better properties with good wear resistance.

So this is one of the very early work that our group has conducted when magnesium based composites where steel receiving significant attention in the academia. So therefore why magnesium silicon carbide composites, it was expected at that point of time that magnesium silicon carbide composites can potentially replace that aluminium silicon carbide composites.

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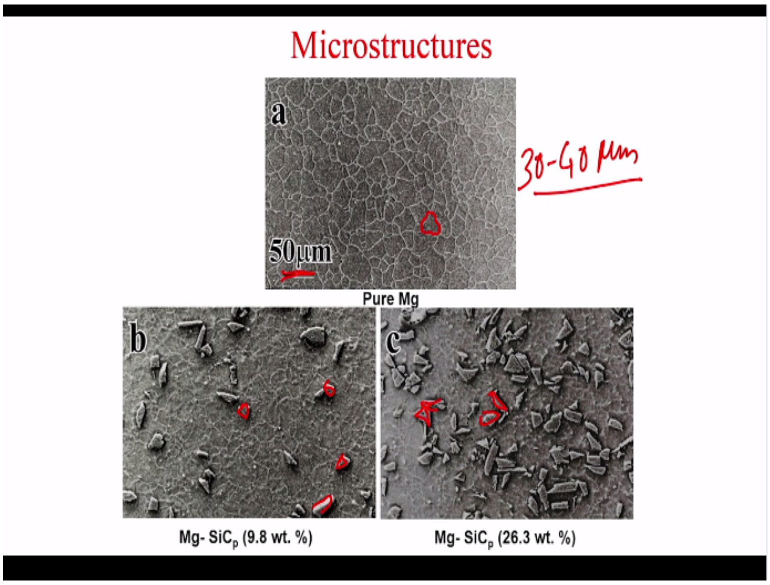


Now this is the microstructure of the as-cast material, what you see here this is the pure magnesium, so it has a (()) (07:39) grain structure and if you look at the scale it is 50 micron and the same scale is valid for all 3 images here, all 3 microstructures. So what you see here that magnesium grain size is roughly around 30 to 40 micron that is the grain size okay, so that is the most of the grains of magnesium.

Now when you add 9.8% silicon carbide or 26.3% silicon carbide, you see that let silicon carbide particulates dispersed in the matrix okay and these silicon carbide particulates that are essentially expected to improve the wear resistance of these materials.

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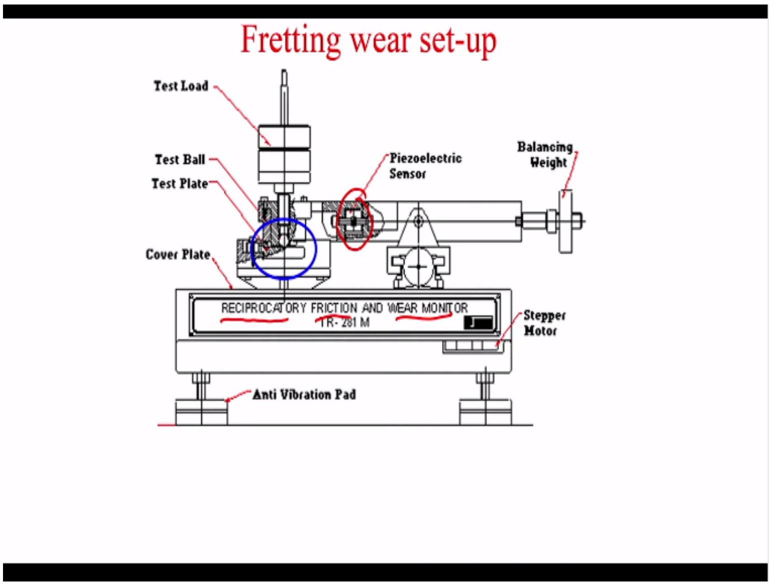


Now this is the fretting wear testing that our group has used before and essentially this is reciprocatory friction and wear monitor. It has a piezoelectric sensor here which is used to record the frictional force.

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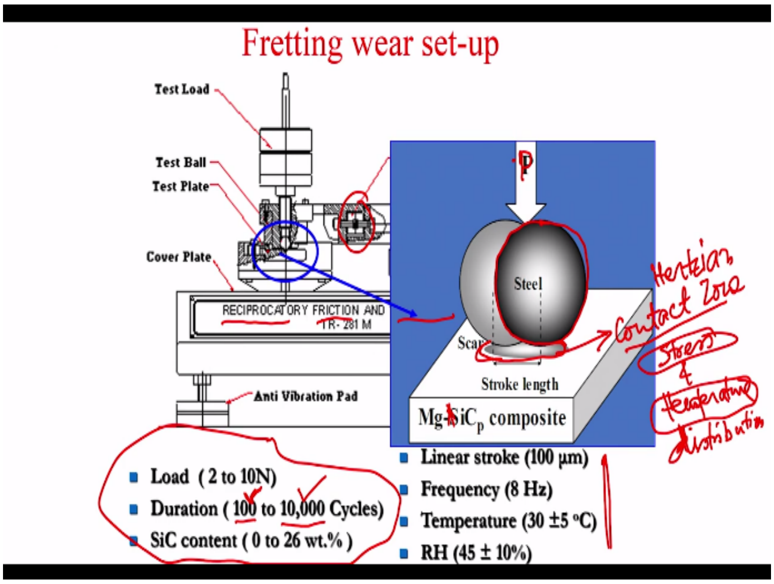


And if you now have a little bit larger view of this particular circular region so we have used steel as a ball and steel as a matting material and then you have magnesium (()) (09:04) silicon carbide composites right as a flat material. Now typical stroke length is let us say 100 or 200 micron and therefore you can see this is the region where which is the contact zone so from our earlier contact zone or scientifically it is known as Hertzian contact zone.

Now from our earlier lectures if you recall this is the region where you have a stress distribution and you have a temperature distribution and stress and temperature in this particular region is not the luminal stress or is not the ambient temperature but it is a modulated stress and certainly higher temperature in this contact zone. So this load is applied so through their weight and then this particular this motion is actuated, relative motion is actuated at the ball and flat interface at the sliding contact.

And then accordingly you can see that what is the wear damage that has been imparted to the interface zone. Now what are the different parameters what we call operating parameters is the load is 2 to 10 Newton is varied, duration is cycle duration is 100 to 10,000 cycles and silicon carbide content as I mentioned in the last slide it is around 9.8 and 26.3% that is the silicon carbide.

And our baseline material magnesium without any silicon carbide. I should point out here that why we use the low number of cycles also to investigate the wear mechanics. The reason behind that at the low number of cycles when the wear damage sets in we would like to understand that how with the number of cycles wear mechanics goes through a transition. For example, certain wear mechanisms active in 100 cycles.

But if you go to 1000 cycles that wear mechanics can undergo transition so that as the transition in wear mechanics with wear progression was one of the objectives in this particular study and therefore we have used different number of fretting cycles in this particular study. What is the other constant parameters? These are the operating variables and these are other constant parameters.

Linear stroke length that is 100 micron that is a relative displacement in each cycle fretting cycle, frequency was 8 hertz, temperature was ambient temperature and again relative humidity was 45%. The way we maintain this relative humidity in temperature we kind of place this wear tester in an experimental chamber where we can closely maintain the temperature and relative humidity inside the chamber.

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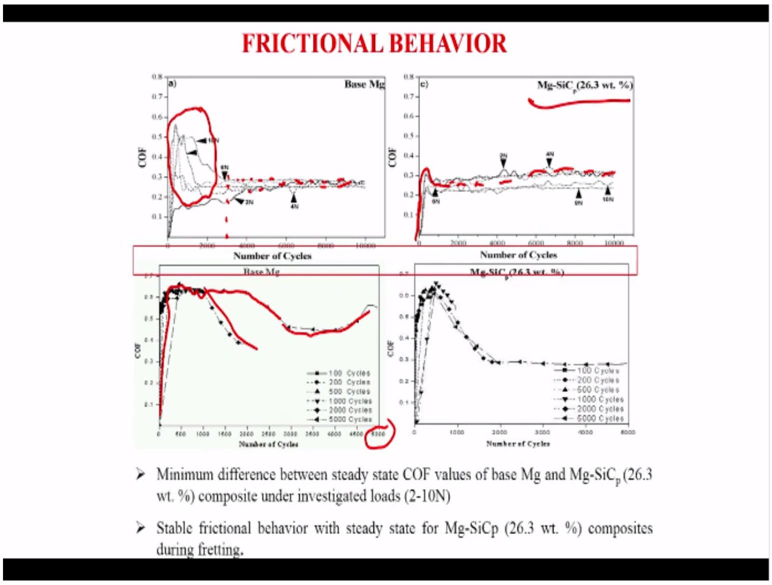


Now this is the frictional behaviour like how coefficient of friction that evolves with number of cycles. It gives you quite an interesting idea. For example, the first case if you look at the magnesium, magnesium that is running in period the friction coefficient increases to very large values. Now after 2000 cycles or 3000 cycles here if you see it drops for magnesium and goes to a steady-state like 0.3.

When you add silicon carbide let us say silicon carbide like 26.3 weight% that is the extreme end of the silicon carbide composites then what you see here that the running in period coefficient of friction does not increase to 0.5 to 0.6 but running in period coefficient of friction goes to around 0.3 and then it reaches the steady-state and it is there as 0.3 as well. So essentially there is not much difference between the steady-state coefficient of friction.

But the way the coefficient of friction evolves with time in terms of number of cycles that is quite different. Second thing that you notice if you want to understand that how the coefficient of friction increases in the first 5000 cycles here you will see that it increases to 0.6 then it slowly decrease and this decrease essentially varies with different number of cycles okay but in case of other composites we did not see much difference.

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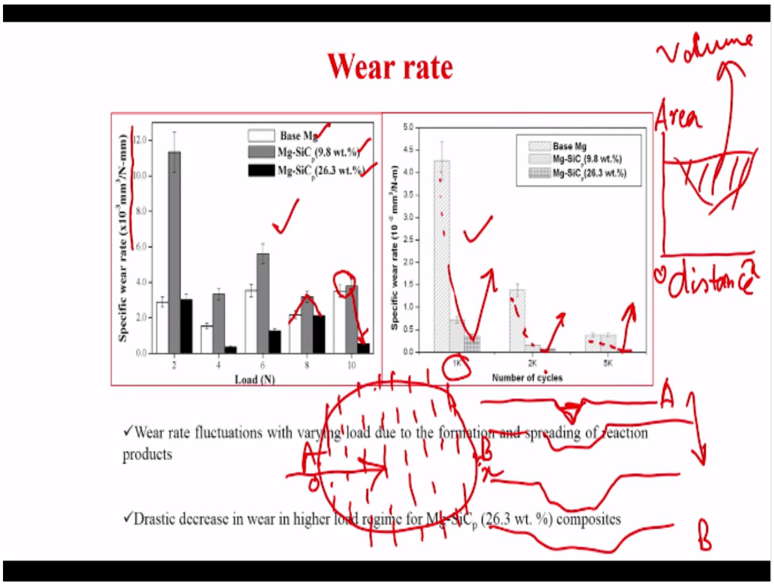


Now in terms of wear rate what you see specific wear rate if you look at the specific wear rate value it is 10 to the power -3 millimeter cube per Newton meter. How this wear rate is calculated? Suppose you have a fretting wear scale like this, I am just explaining you in terms of certain schematic here. Now this is one end of the wear scar, this is another end of the wear scar.

Then, what we do we take some 2-D profile at different parts of the wear scar. In this 2-D profile, what you do, you get this kind of 2-D profile right. As you go from this direction to this direction or this direction to this direction profile depth increase and surface area also increase you understand. So I repeat if you go from point A to point B and this is let us say it is point A and then it goes down and somewhere it is point B.

Then, we will see that fretting wear depth and then wear scar area that progressively increase because the maximum damage is located or is concentrated in the central region. Then, what one can do, one can do this area of the wear scar this area and then they can plot it as a function of distance. So if this is a 0 distance and this is x distance so you can plot 0 versus x. Then, you get some curves right.

And these curves you take area under the curve then you get the wear volume. So this will get the wear volume but how to get the specific wear rate, so that is wear volume/the normal load that is applied*the total fretting distance and total fretting distance how you can get, suppose if you do this experiments up to 10,000 cycles you know what is the frequency of 8 hertz, you know what is the linear stroke length of 100 micron.

So you know that how many cycles that it perform and you know that 8 hertz is the frequency so from there you can calculate that what is the total sliding distance that it has covered. So therefore it is kind of normalized wear rate or specific wear rate and it goes to 10 to the power -3 millimeter cube per Newton millimeter. Now what you see here in terms of the load this if you go to 0% silicon carbide, 9.8% silicon carbide, 26.3% silicon carbide, you see very funny frame that is followed that in almost at all load cases it is increasing at 9.8%.

Then, decreasing at 26.3%, this increase is not significant at 10 load at 10 Newton load but the decrease is significant from 9.8 to 26.3 or from 0 to 26.3. Now this is one information that we got from this load dependence of the specific wear rate. Other information that we can get form specific wear rate as a function of number of cycles. Now what you see at the 1000 cycles, the specific wear rate decreases.

At 2000 cycles, specific wear rate decreases, at 5000 cycles specific wear rate decreases further. So what you notice here, at 26.3% is kind of much better composite in terms of the lowest wear rate even in the initial part of the wear study as well as load dependent wear rate is concerned.

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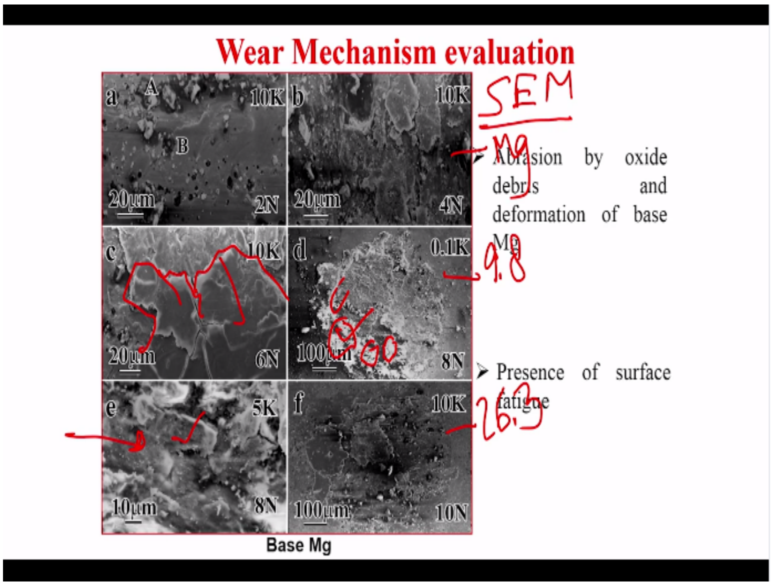


Now one of the major difference the way material scientists or metallurgists they want to understand the wear mechanism and the way mechanical engineers they want to understand the wear mechanism is that material scientists would like to always understand that what is the difference in wear mechanisms and in order to understand or in order to probe into the difference in wear mechanisms material scientists always use extensive microscopic observations.

So these are the observations. This is based on SEM, SEM stands for scanning electron microscope. Now this scanning electron microscope you can see that this is the first one is the magnesium, this is 9.8% silicon carbide and this is 26.3% silicon carbide. Now what you notice as your silicon carbide content is added, there is a clear signature of the tribochemical wear formation and tribochemical layer and also there is a clear evidences of the wear debris particles which are of different size and shape.

And this is the very clear distinction this tribochemical layer is also not very protective because there is lot of cracking in the tribochemical layer. At 26.3% silicon carbide you see this tribochemical layer is much more dense and compact and then sprayed on the total surface. So these are the two mechanisms that we have seen that presence of surface fatigue and then delamination of the base magnesium.

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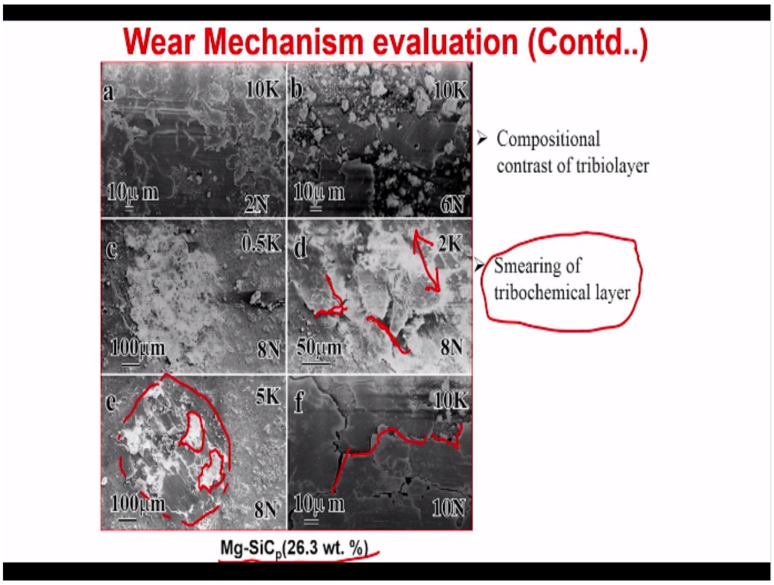


As I said before that we also would like to understand that how this tribochemical layer that sets in at different other composite for particularly magnesium 26.3% silicon carbide composites. You clearly see this is your wear own region right and you see that this tribochemical that appears in the scanning electron microscope in different contrast. This very bright contrast and very dark contrast essentially means they have a compositional difference.

You will also see there is evidences of cracking as you can see so whenever you see any cracking on the tribochemical layer, you can very well perceive that this cracking would lead to decrease in the stability of this particular layer. You can see the evidences of cracking also here. Now in most of the things the fretting directions is like this.

So many times you will see that cracking can be either along the fretting directions or normal to the fretting direction also but overall I repeat that there is a smearing of the tribochemical layer which is observed locally for all the compositions.

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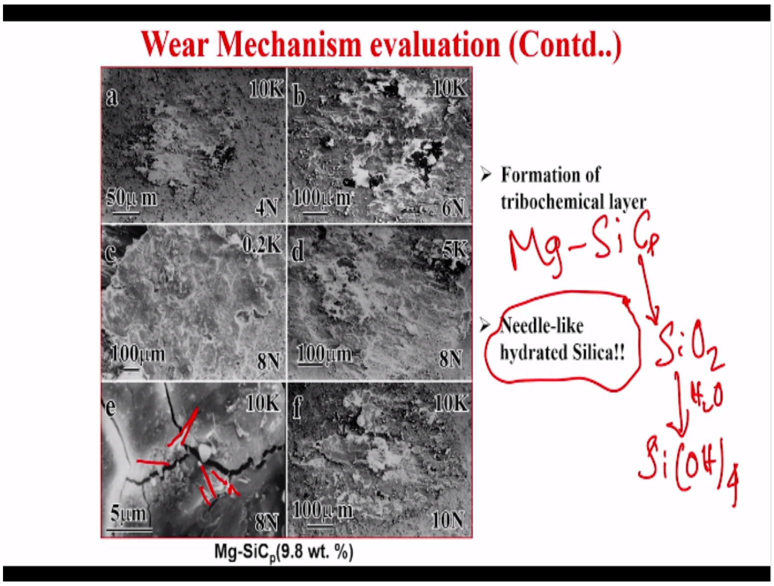


In some of the cases, we have found very needle-like tribochemical wear debris formation. This needle-like wear debris formation is a very interesting observations and mostly the hydrated silica because you remember our composite is magnesium silicon carbide particulates, silicon carbide particulates it can form silica or silica it reacts with H2O it can form as SiOH whole 4.

So all these tribochemical reactions can take place very well in these fretting surfaces and that can lead to this kind of needle-like silica formation okay.

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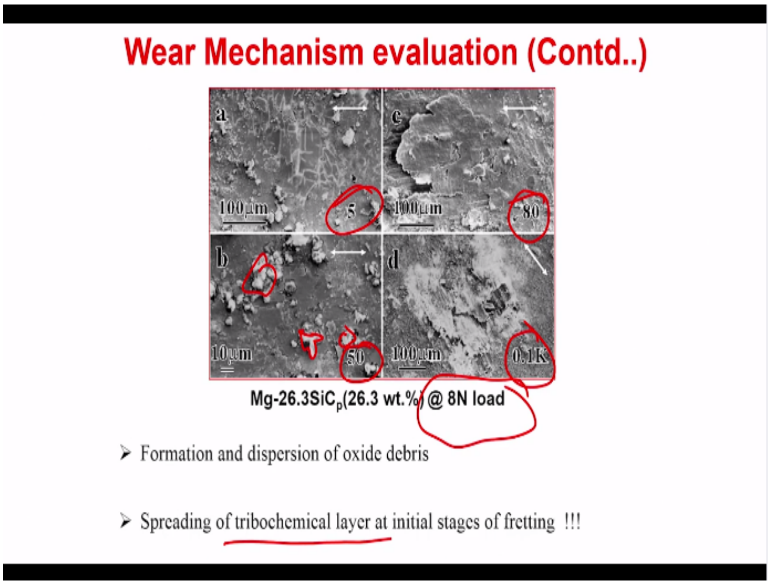


Then, this is other one at very high load of let us say 8 Newton load, we can also see formation and dispersion of the oxide debris so that this kind of oxide debris particles is spreaded and this also the spreading of the tribochemical layer also forms at the very initial number of cycles. You can see 0.1 K means 100 cycles, 5 cycles, 30 cycles. So what you see that as I said that our motivation was to understand the transition in the wear mechanisms during wear progression.

Therefore, we have done several interrupted testing like after 5 cycles we stopped the fretting wear, after 30 cycles we stopped the fretting test, after 50 cycles we stopped the fretting test and then observed that what is the dominant wear mechanism and which kind of wear mechanism sets in at the very early stage of the fretting wear.

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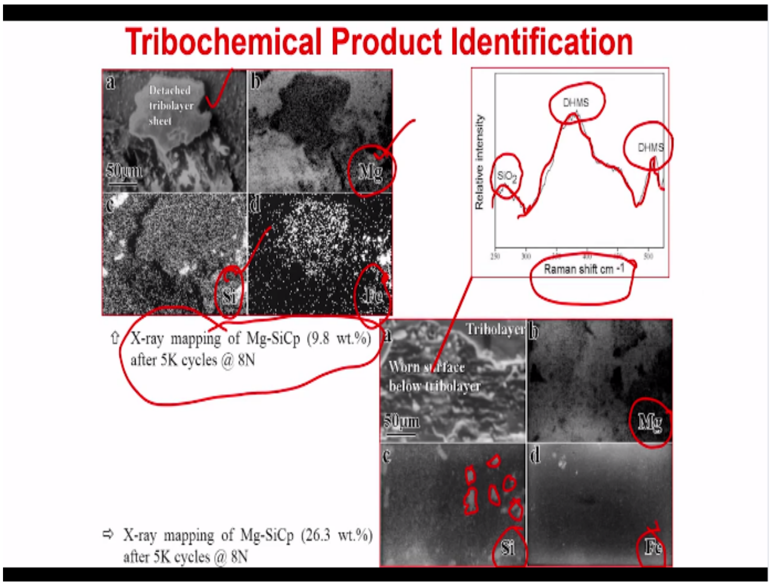

Now in the scanning electron microscope you can also do x-ray mapping and this is the compositional mapping which will give you an idea that what is the chemical nature of the tribochemical wear debris. Now this is the actual area of the tribo layer, so we have done 3 elements, magnesium, silicon and iron. Why iron? Because iron can very well come from the steel body that is why we have done iron.

Magnesium and silicon is a base material. Similar things we have done for the magnesium silicon carbide composites with 26% reinforcement. So you can see very clear signs of the silica-based tribochemical layer formation here whereas iron content is fairly low. So we have also done Raman spectroscopy. So this Raman spectroscopy is a tool which is used for many times which is used many times to confirm the chemical nature of certain tribochemical oxides.

So here you can see there is very weak signal of silica and also there is another interesting observation we have got, it is the very clear peak Raman spectra Raman band for this DHMS. What is DHMS?

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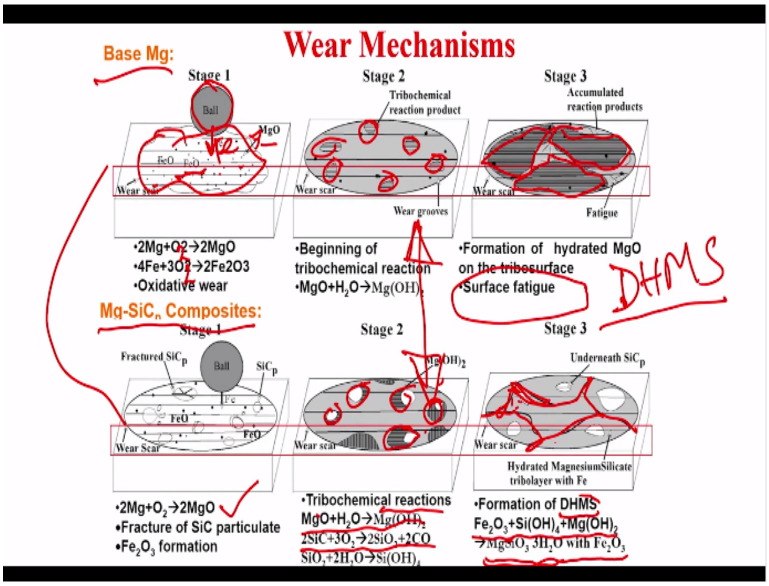


I will come back to in this particular slide here. So essentially DHMS stands for hydrous magnesium silicate and D stands for dense so dense hydrous magnesium silicate has a chemical composition MgSiO3 3H2O. So this is the extremely an important slide which essentially summarizes the differences in the wear mechanisms of two different materials, one is the baseline magnesium and one is the magnesium silicon carbide composites.

What you see here that this is a ball, steel ball and this is your iron which is transferred and this is the wear scar okay. So you have a magnesium oxide and you have iron oxide, so this magnesium oxide and iron oxide it forms on this particular thing on this particular wear scar and there is also tribochemical reaction product which you see that is taking place in the stage 2. In the stage 3, we have seen that there is wear scar is completely covered by the fatigue as well as the accumulated reaction products.

So this is the stage where surface fatigue plays an important role. In the magnesium silicon carbide composites, we have also similar oxidation 2Mg+O2 is 2MgO and further tribochemical reaction sets in magnesium oxide like MgO+H2O forming magnesium hydroxide. Silicon carbide also gets oxidized to form silica and as I said in the few minutes back that silica can react with hydrogen water to form SiOH whole 4.

So all these reactions takes place and finally the Fe2O3 that is formed to the transfer of steel iron and the silicon hydroxide as well as magnesium hydroxide. Now all these things it can form is magnesium silicate. So DHMA stands for dense hydrous magnesium silicate. So like this particular case the stage 1 is kind of more or less similar but stage 2 there is a difference if you go to the stage 2 between the baseline metal and composite, you can see here very clearly in this stage 2 that magnesium oxide reacts with magnesium hydroxide.

But at the same time silicon carbide is getting oxidized and then stage 3 is very different from the baseline oxide where this entire wear scar is completely covered by the dense hydrous magnesium silicate and there is also I have shown the evidences of cracking that what we have observed in the last few slides. If you recall that some of the major evidences of this cracking here, you can see that.

So if there is cracking, there is at every potential that this chunk of the materials of the own surfaces will be lifted off and will be coming out and then form a wear debris particles. So this is the entire wear mechanism study.

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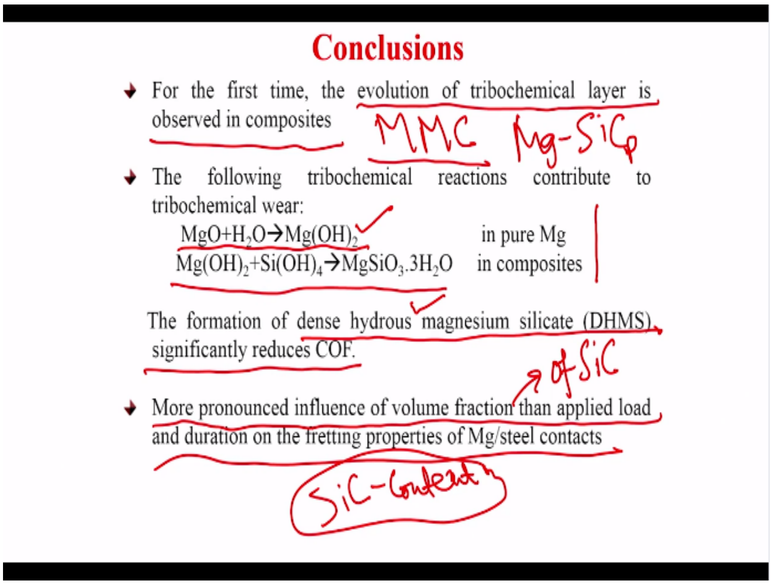


So to conclude this particular case study when we reported this particular case study at least couple of years back that was perhaps for the first time that the evolution of tribochemical layer is observed in case of metal matrix composites. As I said magnesium metal matrix composite is something that time we started as a new and these samples were essentially supplied by Professor Manoj Gupta of National University of Singapore.

He is a leading expert in this magnesium based composites and I believe that he has worked on several magnesium based composites and other key conclusions were in case of magnesium pure magnesium or baseline magnesium the major tribochemical reaction is magnesium oxide which reacts with water to form magnesium hydroxide and magnesium hydroxide which further forms with silicon hydroxide to form magnesium silicate 3H2O.

And dense hydrous magnesium silicate that is one of the new observations and that we believe significantly reduces the coefficient of friction. The third and last conclusion is that we have observed also more pronounced influence of volume fraction of silicon carbide. So this is the volume fraction of silicon carbide then applied load and duration in the fretting properties.

So what it means that silicon carbide content is by far is most important than the load in this particular wear system. So one can tailor the silicon carbide content and perhaps one can do 20 or 30% silicon carbide and that is the maximum and then it will experience very low wear rate not only at low load but also at high load. Thank you.