Friction and Wear of Materials: Principle and Case Studies

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Lecture - 20
Sliding Wear of SiC-WC Composites

So welcome all. Today we would like to discuss the silent results from Sliding wear behavior studies of silicon carbide, tungsten carbide composites. So as explained in one of the earlier lectures silicon carbide is a ceramic material having superior combination of properties, but the properties can be further improved by reinforcing with other phase.

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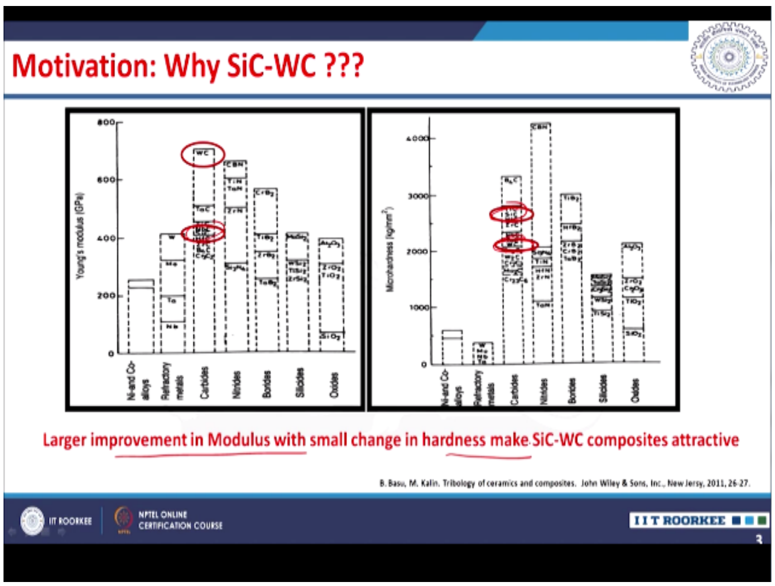

Among the silicon carbide based ceramic composites we can see the Young's modulus of the tungsten carbide is the; Young's modulus of tungsten carbide is much higher than the silicon carbide whereas the hardness is slightly lesser than the silicon carbide hardness. So if you have the composite of silicon carbide tungsten carbide composite we can expect improvement in the modulus with a small change in the hardness. So such a composite will be attractive for several tribological applications.

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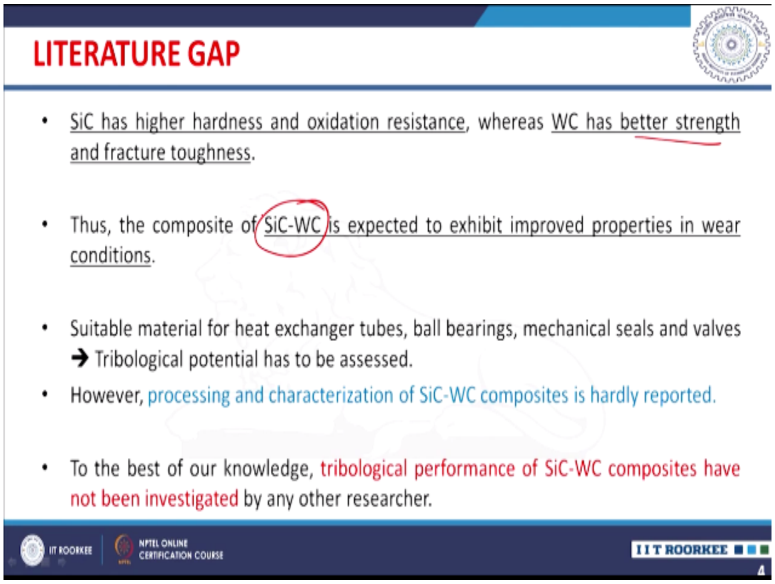

However, our literature study indicates that such a material is not studied for the tribological behaviour. So particularly the silicon carbide has higher hardness and oxidation resistance whereas tungsten carbide has better strength and fracture toughness, so the composite of silicon carbide tungsten carbide is expected to exhibit improved properties in wear conditions.

However, the processing and characterization of dense composites of silicon carbide tungsten carbide is a difficult task. So very less study is are reported silicon carbide tungsten carbide composites. Particularly, dense silicon carbide tungsten carbide composite preparation is not yet reported. In addition to that that, the tribological performance of dense silicon carbide tungsten carbide composites has not been investigated by any other researcher. So in this context, the major objectives of the present studying which will be discussed in the today's class.

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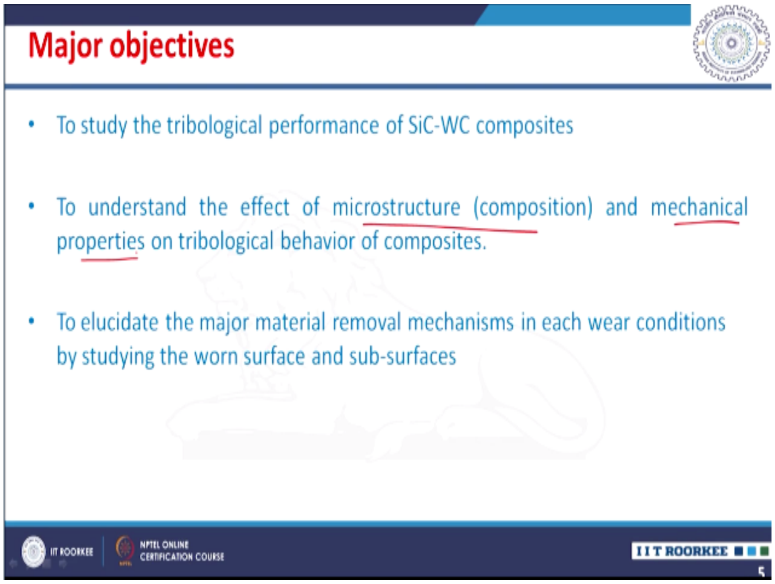

To study the tribological performance of this silicon carbide tungsten carbide composites, and to understand the effect of microstructure by changing the composition and as well as mechanical properties and the tribological behavior of this composites. Particularly, to illustrate the major wear mechanisms in which wear conditions by studying the worn surface and sub-surfaces. So these silicon carbide tungsten carbide composites were prepared at the University of Seoul with the support Prof. Young-Wook Kim of university of Seoul.

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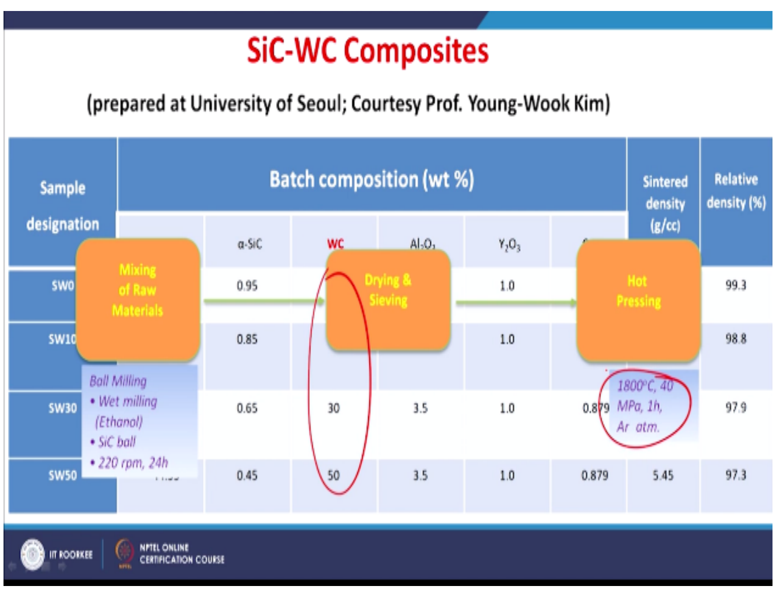

So for composites are selected for the present study with varying tungsten carbide content from 0 to 50 weight percent, so 0, 10, 30, 50 weight percent; tungsten carbide containing silicon carbide, ceramic composites are prepared with beta silicon carbide with a small amount of alpha silicon carbide and aluminum oxide, yttrium oxide, calcium oxide as a additive systems.

So these were prepared by Hot Pressing. So before hot pressing this batch powder were mixed and then dried and sieved followed by hot pressing at 1800 Celsius and 40MPA for one hour in organ atmosphere, so the sintered density of these materials are 98 to 99%.

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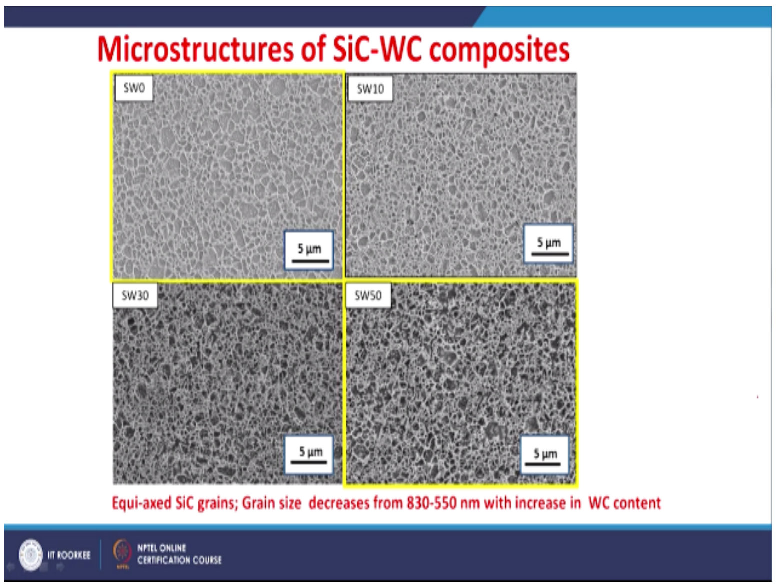

The microstructure of sintered silicon carbide composites exhibit almost equiaxed grains of silicon carbide. A very, very less presence of any elongated grains. So these almost equiaxed grains size decreased from around 830 to 550 nanometers with increase in the tungsten carbide content from 0 to 55%.

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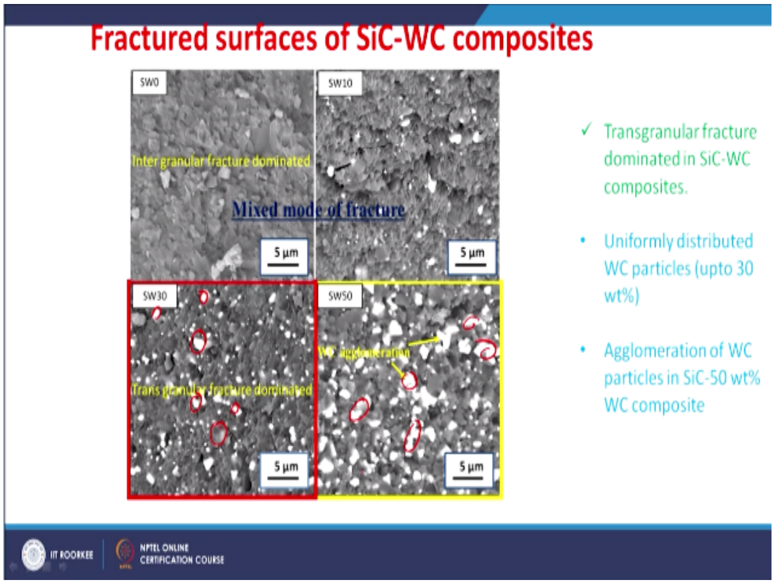

The Fractured surfaces of these composites show mainly the intragranular fracture dominating when no tungsten carbide was added. This simply pulling out this SiC grains. Then tungsten carbide is added Transgranular fracture is been dominated. So you can see the silicon carbide grains are fractured, so these difference in the mode of the fracture from intragranular to transgranular mode is going to help in the improvement of properties.

Now with respect to the tungsten carbide content you can see the uniformly distributed tungsten carbide particles in the silicon carbide metric. Whereas you can also see sometime agglomeration present when you have larger amount of tungsten carbide content. So this SiC with 50 weigh percent tungsten carbide composite showing agglomeration of this tungsten carbide particles.

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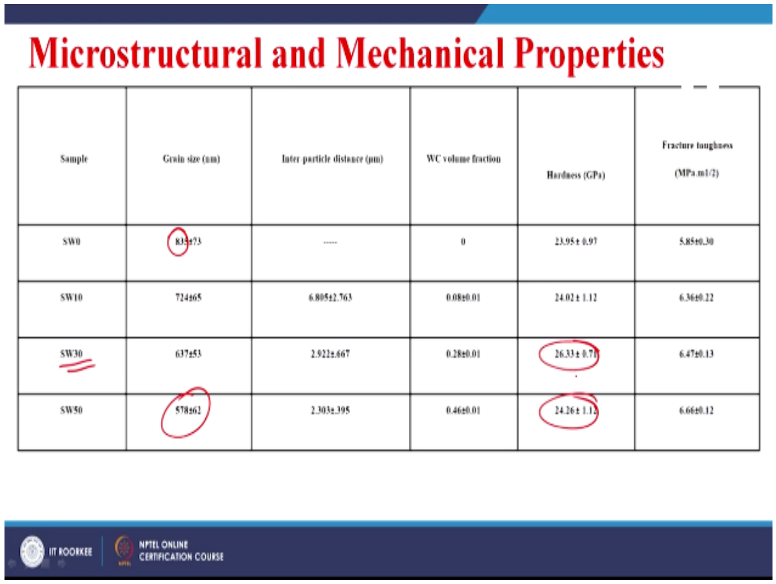

Sample	Grain size (nm)	Inter particle distance (µm)	WC volume fraction	Hardness (GPa)	Fracture toughness (MPa.m1/2)
SW0	835±73	-----	0	23.95 ± 0.97	5.85±0.30
SW10	724±65	6.805±2.763	0.08±0.01	24.02 ± 1.12	6.36±0.22
SW30	637±53	2.922±.667	0.28±0.01	26.33 ± 0.7[illegible]	6.47±0.13
SW50	578±62	2.303±.395	0.46±0.01	24.26 ± 1.12	6.66±0.12

So the mechanical properties are studied for these composites. The hardness increases up to 30 weight percent tungsten carbide whereas it slightly decrease with 50 weight percent whereas fractured toughness improves from 5.85 MPa root meter to around 6.67 MPa root meter. So if you look at the correlation between the Microstructural characteristic and the mechanical properties the grain size decreased from 835 nanometers to 578 nanometers with increase in tungsten carbide content.

The inter-particle distance also decreased with larger amount of tungsten carbide in these composites. So it indicates that while sintering the grain growth was restricted by the presence of larger amount of tungsten carbide content. So it actually reflected in the properties particularly hardness showed an increase in the for the silicon carbide 30% tungsten carbide composite and the fracture toughness continuously increased from 5.85 to 6.67 Mpa root meter.

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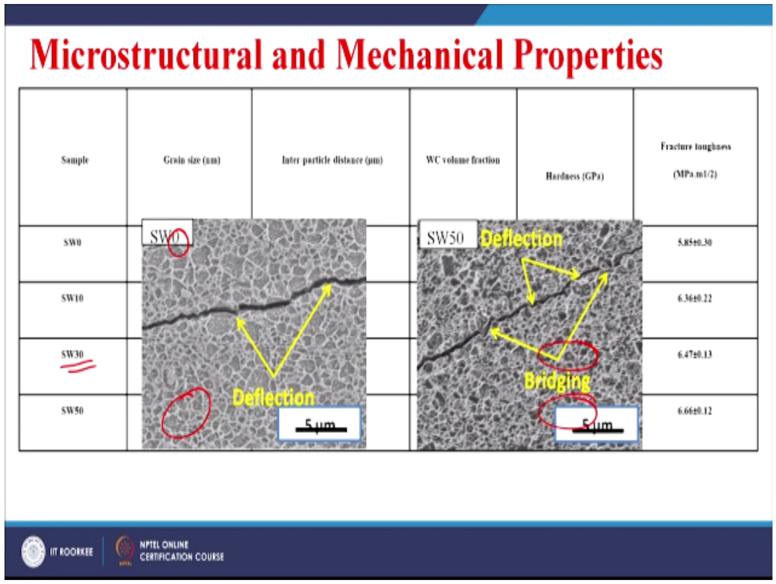

So this fractured toughness improvement is very important for any structural applications. So it is to be studied, so after Vickers indentation at the adjust of these indents the cracks are propagated and we can see here when no tungsten carbide was added the deflections for the cracks are minimal whereas the deflection are the bridging or actually improved when you have tungsten carbide content; particles. So these tungsten carbide particles they improve the fracture toughness by bridging of the crack or the deflection of this cracks.

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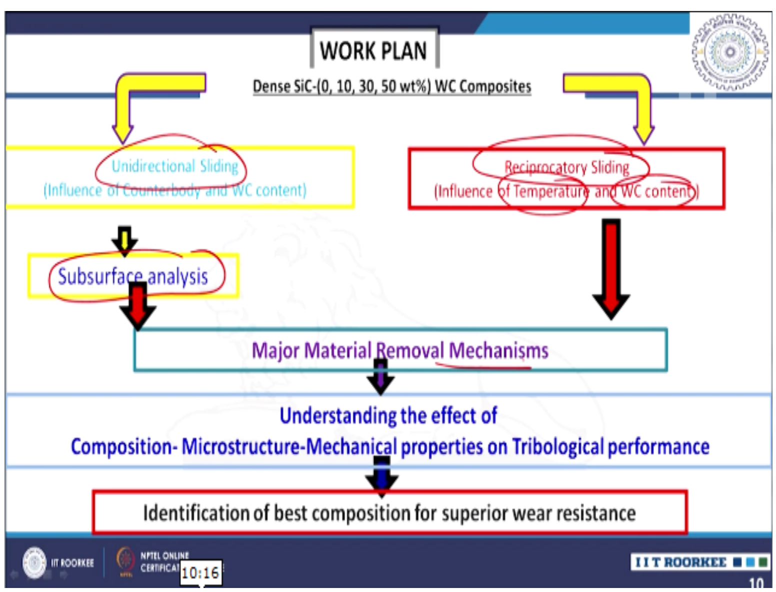

So with this introduction of this material the tribological performance is systematically studied in two different sliding wear conditions. For this one unidirectional sliding wear study was done and other reciprocatory sliding study was done. So in the unidirectional sliding wear study the counter body influence and the tungsten carbide content were particular studied whereas in the reciprocatory sliding condition the temperature of the sliding test and tungsten carbide content were particularly studied.

In addition to this sliding wear behaviour unidirectional a major focus is given for the subsurface analysis to find out the origin of the material removing mechanism. Basically, the major aim of this particular study is to elucidate the major material removal mechanisms.

So that we can have an understanding and the very important relation of the composition of this composite that is tungsten carbide content variation that reflects into microstructure, and the microstructural influence and the mechanical properties under tribological performance. So the particular study is to understand the effect of composition or microstructure and the mechanical and tribological behavior. And to identify the best composition for the superior wear resistance.

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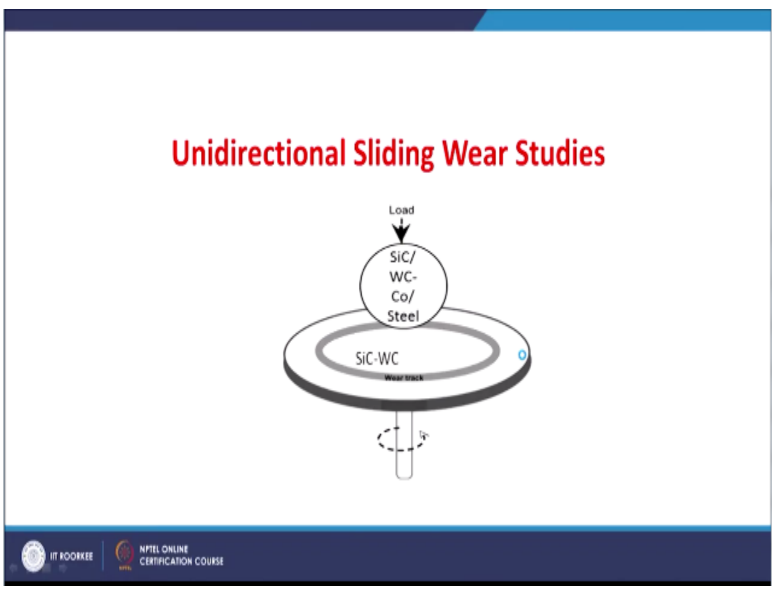

So let us go through the silent results obtained in unidirectional sliding wear studies.

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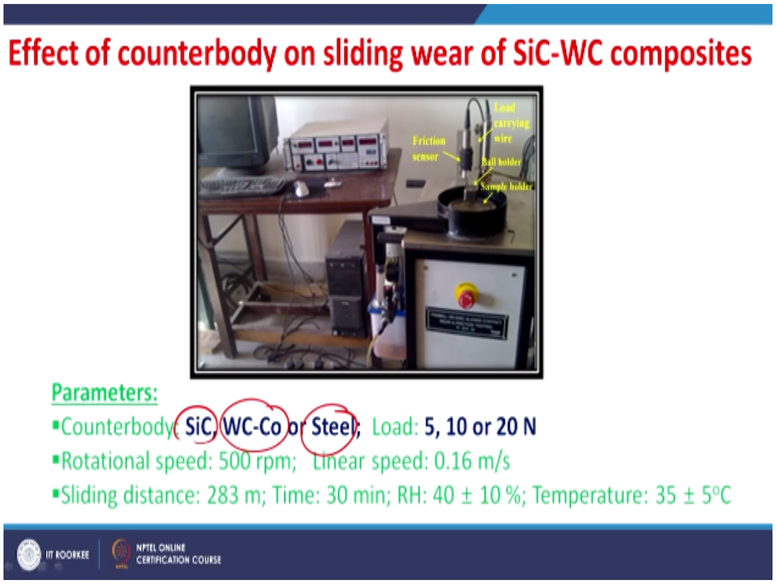

So mainly three different counter bodies of silicon carbide ceramic and tungsten carbide cobalt which is called a cermet and steel were used as a counter body. And three loads separately 5, 10, 20 Newton loads were applied with a combination of other parameters which were kept constant. For this the ball on this tribometer was used, so the disk is the specimen which is the silicon carbide tungsten carbide composite whereas the ball is changed from silicon carbide to tungsten carbide cobalt or to steel.

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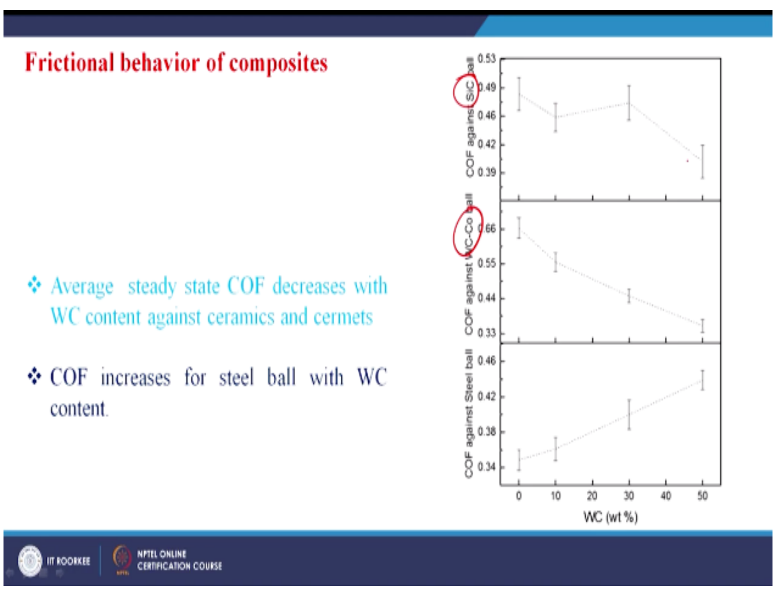

And the Friction was measured and the wear was determined. So the friction coefficient shows the average coefficient of friction actually decreases with against silicon carbide or this tungsten carbide cobalt ball. Whereas as against steel it actually increases because the surface is actually changed at the content so there is a friction behavioral change.

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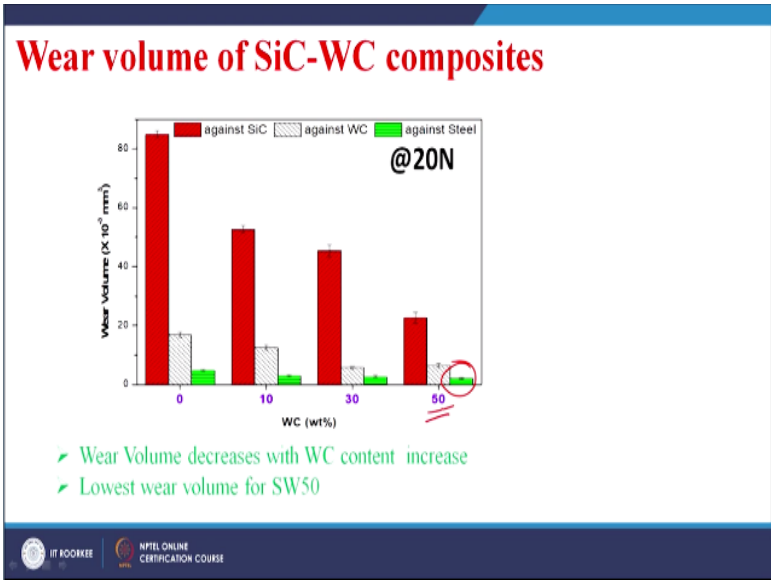

Let us understand it further. When wear volume was measured the wear volume was measured as I explained in the previous class the Profilometry was use to read the surface profiles in a two-dimensional way and over a particular; over a slide distance this was integrated and the wear volume was determined.

So you can see the wear volume of these composites having 0, 10, 30 weight percent tungsten carbide content. So against to silicon carbide against to tungsten carbide, that is tungsten carbide cobalt and then against to steel, so the wear volume decreased with tungsten carbide content for any counter body, for any composite against any counter body. Whereas the lowest wear was observed with the silicon carbide containing 50 percent tungsten carbide.

So at a particular load the wear volume decreased with tungsten carbide increase and the lowest wear was obtained with SW50 composite. Regarding the effect of the counter body the wear volume was highest for the composites 1 again the silicon carbide ball. Whereas the wear volume was the lowest for the composite one again a steel volume. So tungsten carbide cobalt data is in between. So the behavior can be understood by studying the one surface of this composites.

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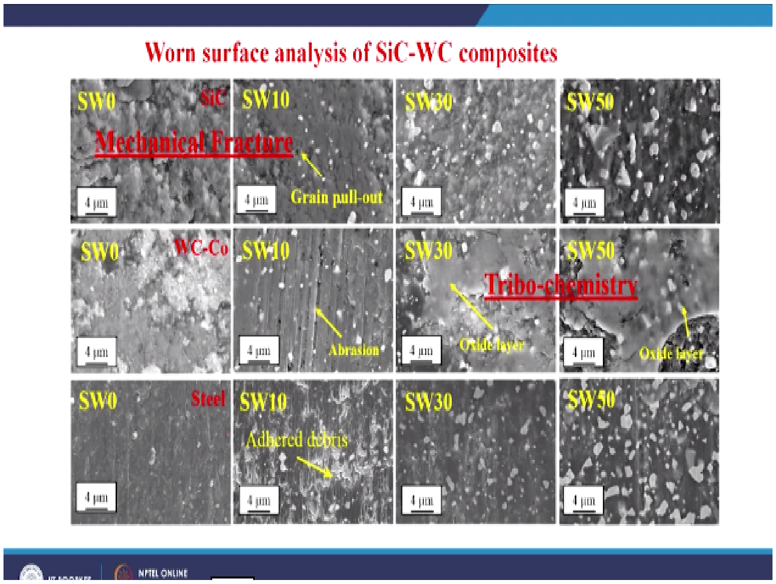

So you can see here as the tungsten carbide content actually increases you can see the mechanical fracture is more. Again is to silicon carbide and tungsten carbide and the steel there is a change in the major mechanism of the material removal. Particularly, when these composites were worn for again a silicon carbide tungsten carbide cobalt, silicon carbide or tungsten carbide cobalt you can see the signatures of the mechanical fracture, you can see the grain pull-out which happens by the cracking, so the worn; the grains are pulled out so they get fractured.

But these white particles are tungsten carbide removed from the surface. But if you look at the composites worn again a tungsten carbide cobalt with a lower content of tungsten carbide containing composite it show mainly the abrasion. But as the tungsten carbide content is increased you can see the presences of particular layer. This layer dominantly covers the surface particularly when you have the highest tungsten carbide content.

But when you see the composite worn surfaces which were worn again as to steel again they show the debris and then fracture and removal of this tungsten carbide particles. So there is a change from the mechanical fracture to Tribo-chemistry when there is a change in the tungsten carbide content or there is a change in the counter body. So to summarize the wear mechanisms against different counter bodies as a function of tungsten carbide content.

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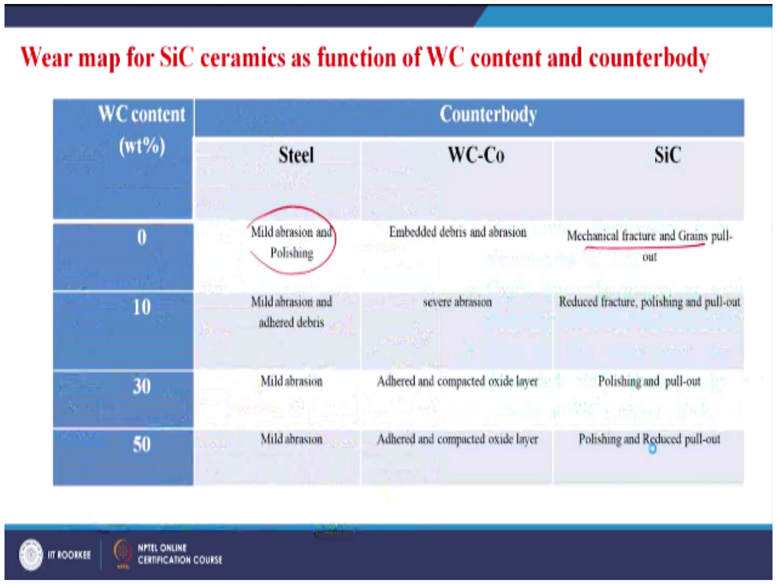

Wear map for SiC ceramics as function of WC content and counterbody

WC content (wt%)	Counterbody		
	Steel	WC-Co	SiC
0	Mild abrasion and Polishing	Embedded debris and abrasion	Mechanical fracture and Grains pull-out
10	Mild abrasion and adhered debris	severe abrasion	Reduced fracture, polishing and pull-out
30	Mild abrasion	Adhered and compacted oxide layer	Polishing and pull-out
50	Mild abrasion	Adhered and compacted oxide layer	Polishing and Reduced pull-out

The abrasion and polishing is observed when you do not have any tungsten carbide content and worn against to steel. So when the tungsten carbide content is increased you have adhered debris and the debris are interrupt inside the grubbs. And against to tungsten carbide cobalt this embedded debris and abrasion which becomes sever abrasion when tungsten carbide content is increased.

But as the tungsten carbide content is further increase to 30 or 50 weight percent you can see there is s compacted layer which adheres on the surface. Against to silicon carbide again there is only grain pull-out and fracture only change in the fracture is observed with increase in the tungsten carbide. So with an increase in the tungsten carbide content the fracture is reduced and it becomes more polished and reduced pull-out.

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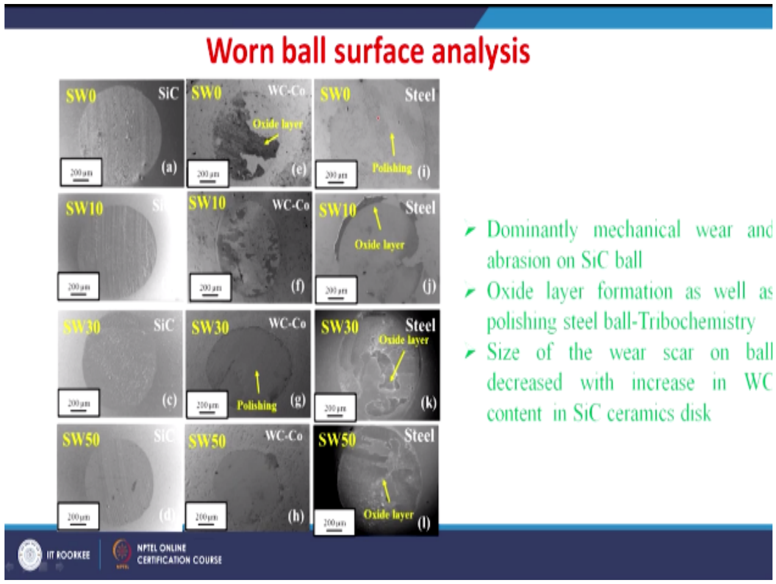

To understand the actual mechanisms, we need to also study the counter body worn surfaces. So you can see the counter body which is a steel so the impression is a circular impression after the wear. The size of the wear scar on the ball decreased with increase in the tungsten carbide content in the silicon carbide ceramics disk. So dominantly there is a mechanical wear and abrasion and the silicon carbide ball.

Whereas in oxide layer formation as well as the polishing is observed against the tungsten carbide or on the balls of tungsten carbide or the steel. So the ball surface analysis show the presence of the Tribo-chemistry on the tungsten carbide cobalt balls or the steel balls. Whereas the silicon carbide balls they do not show any Tribo-chemistry. It is simply the fracture or you can see abrasion and the removal of this material by fracture.

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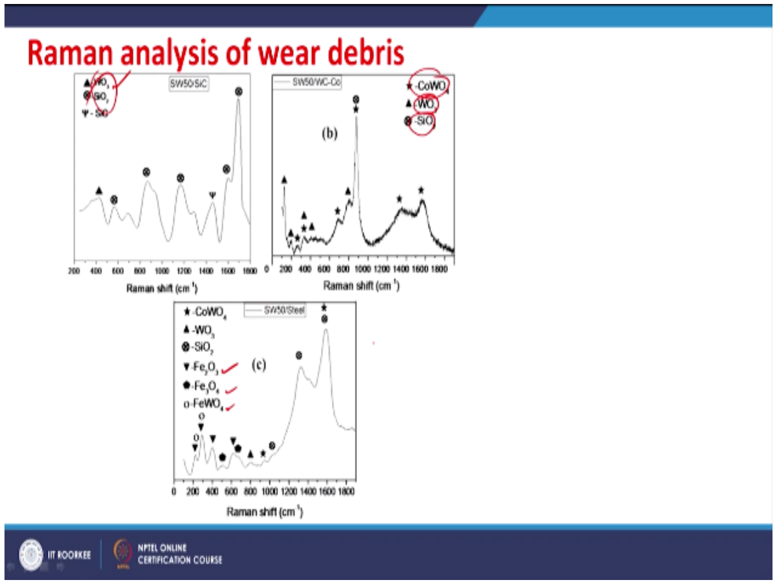

So in order to understand the chemistry difference on the surface worn against to different counter body, the Raman Analysis was done. And the Raman analysis shows different product form as a debris, so the debris against the silicon carbide you can see the oxides of this silicon carbide, the oxides of silicon and tungsten.

So generally when the harder counter body is sliding over the disk surface because of the harder indenting points, so the material is removed and then the material is subjected to oxidation in a normal ambient conditions of sliding. So you can see certain oxides also forming. Against to tungsten carbide cobalt also you can see the tungsten oxide, silicon oxide and the cobalt tungsten oxide debris. And against to steel in addition to this oxides we also see certain oxides of iron and iron tungsten oxide.

So it actually indicates, there is a chemistry difference in the debris formed when these composites were subjected to sliding against different counter body. The friction is more when these were worn against steel because of the presence of the harder oxides of this iron or iron tungsten oxide. And these iron tungsten oxide are not present in the other conditions, so you do not have such an increase in the friction.

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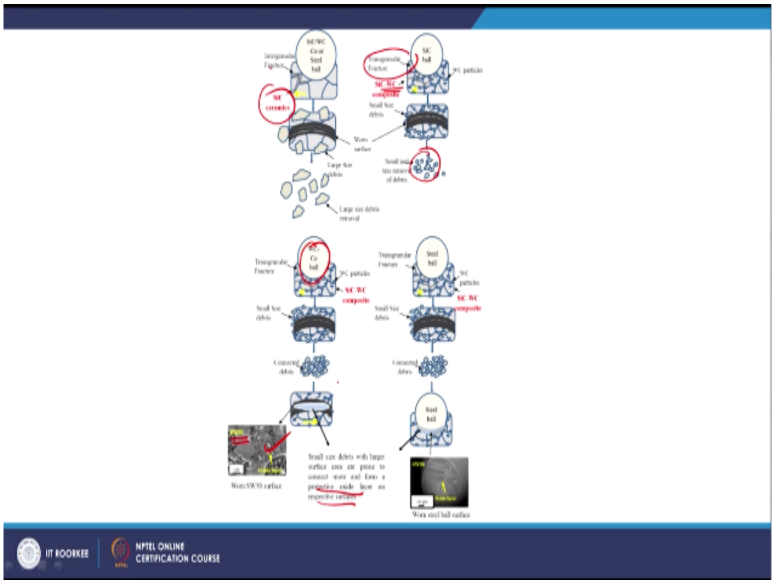

So summarizing the silicon carbide ceramics when you do not having any tungsten carbide so they just fracture by intragranular fracture, intrafranular mode. So this is actually same against to silicon carbide or tungsten carbide cobalt or steel ball. So the larger grains came out as a debris and when the silicon carbide containing some tungsten carbide particles the composite shows a decrease in the size of the grain, so the debris also will be smaller in the size.

So the fracture also we observed change dominantly from intragranular to transgranular when you have the tungsten carbide particles in a silicon carbide ceramics. Now if you see the effect of the counter body against to tungsten carbide cobalt ball these composite against fractured by the transgranular mode way. But the size of the debris because of the finer sign of the debris and also with increase in tungsten carbide content in the composite particularly this SW50 or SW30.

You can see this smaller debris with a larger surface area are more prompt to connect and then form a protective oxide layer like this so you get a decrease in the wear. In case of the steel ball these composites again they fractured by the transgranular mode and the smaller size of debris, smaller size debris they collect each other and form a layer and the layer is actually observed on the ball surface.

So the layer is observed either on the ball surface of the steel or on the disk which was worn against the tungsten carbide cobalt they show certain layer, whereas a layer is not observed when these composites were worn against to silicon carbide, against to silicon carbide it is purely the fracture. The material is removed only by the mechanical fracture and then the resultant grain pull-out.

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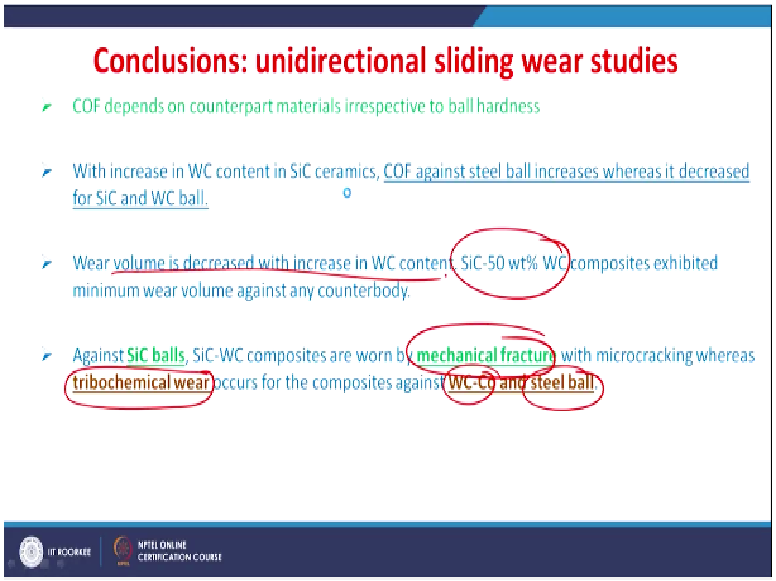

So the major results from the unidirectional sliding wear study are like this. The coefficient of friction depends on the counterpart materials irrespective of their ball hardness. With increase in tungsten carbide content in silicon carbide ceramics the coefficient of frication against to steel ball increases whereas it decrease for other silicon carbide or tungsten carbide cobalt ball. Wear volume decreased with increase in tungsten carbide content.

And the silicon carbide 50 weight percent tungsten carbide composite exhibited minimum wear against any counter body. Regarding the mechanical, regarding the major mechanism of material removal against to silicon carbide ball the silicon carbide tungsten carbide composites are worn by purely mechanical fracture with micro-cracking.

Whereas tribochemical wear is dominating for the composites worn against to tungsten carbide cobalt or the steel ball. So there is a difference in the mechanism of material removals so there is a difference in the friction and the wear. So this actually indicated very important information. That when the silicon carbide tungsten carbide composites or subjected to different counter bodies we have a different wear mechanism dominating so that results into the performance difference.

Amongst the three counter bodies the silicon carbide counter body showed when we use the silicon carbide counter body purely mechanical fracture dominating. So it is very important to understand the origin of such a mechanical fracture. So we selected these silicon carbide tungsten carbide composites worn against silicon carbide ball only where there is a purely dominantly mechanical fracture for a further studies of the subsurface analysis.

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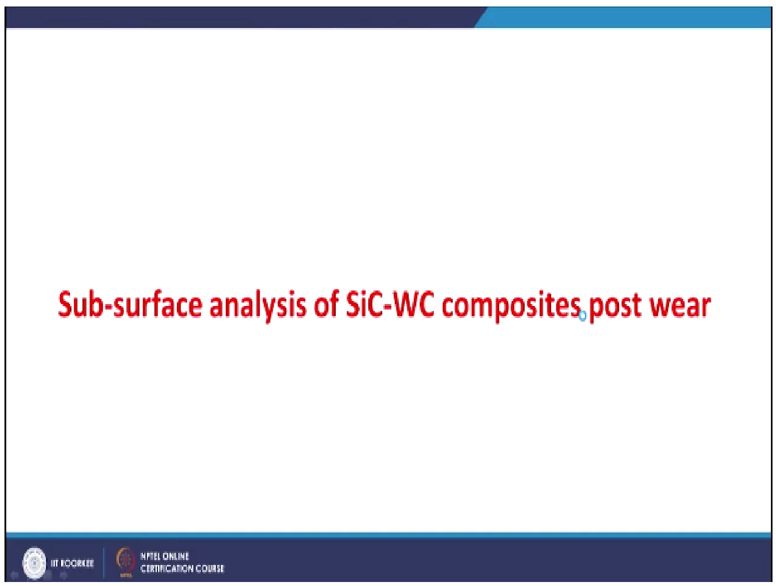

The subsurface analysis study is very important to identity the origin of a such a fracture. So we purposefully note taken these silicon carbide tungsten carbide composites sliding wear studies against the tungsten carbide and steel ball where there as the tribo-chemistry. So these subsurface analysis study were possible with the support from Prof. Amartya Mukhopadhyay of IIT-Bombay. So we can see here the subsurface analysis was done by using an combination of a focused ion beam with T-Young analysis.

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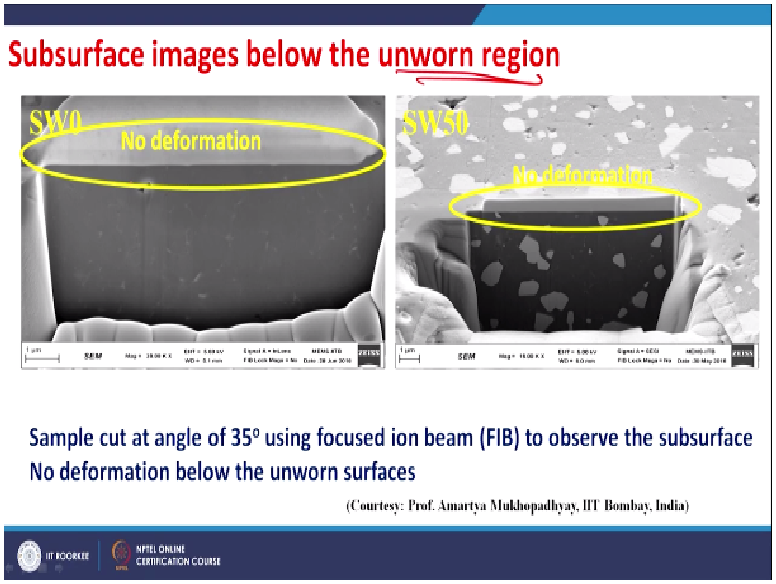

Sample was cut at an angle 35 degree using a focused to observe the subsurface. So the unworn regions of the sample they do not show any deformation whether it is a silicon carbide without having any tungsten carbide or with having any tungsten carbide. There is no signature for any deformation.

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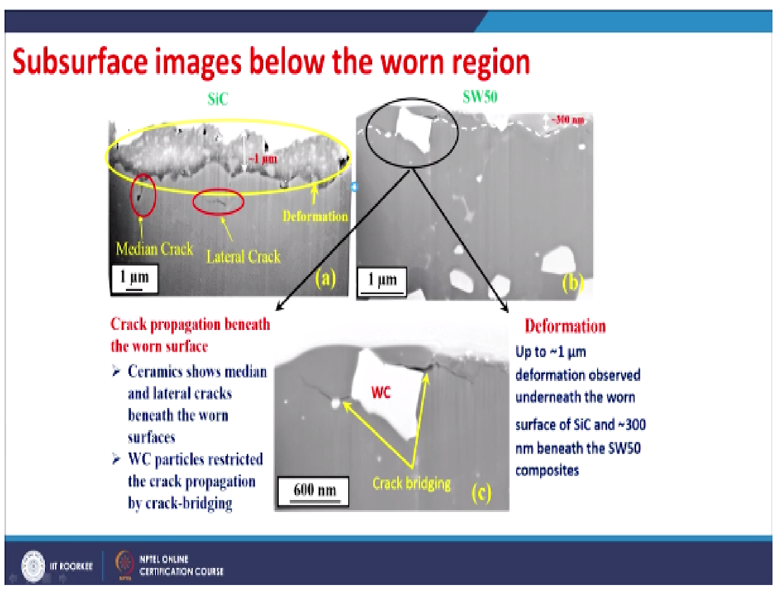

Whereas when these composites are worn you can see lot of difference in the subsurface regions. So when it is only silicon carbide you can see this damaged zone is around 1 micron meter. In case of composite it is only 300 nanometers. So the, there is a resistance against the damaged at the subsurface when you go for the composite. In addition to that we can also see several cracking signatures here.

So generally the ceramic show median and lateral cracks beneath the worn surfaces, it actually follows again the classical linear fracture mechanics. When they harder and sharper content slides over surface particularly the brittle surface the median lateral, median or lateral cracks are generally found.

But if you can see this difference between the subsurface images of these carbide ceramic and silicon carbide tungsten carbide composite, the tungsten carbide particles restricted the crack propagation by the crack bridging right. So this essentially show there is a benefit when you go for a composite right from restricting the crack propagation. So this can be illustrated schematically.

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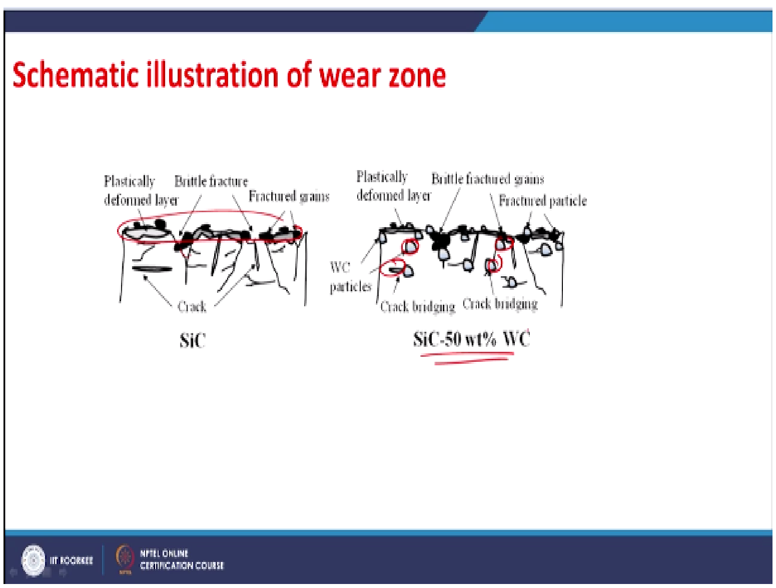

The upper region generally have a plastically deformed region and just below that you have a fracture region so the fracture region is characterized by this cracking whether it is median or the lateral cracking. When you have a tungsten carbide particles these particles result into crack bridging or the crack deflection that improves the resistance against the fracture so you get a lesser wear also.

So if you can recall these silicon carbide tungsten carbide composite shown wear resistance than the silicon carbide ceramic because of this resistance against the crack propagation.

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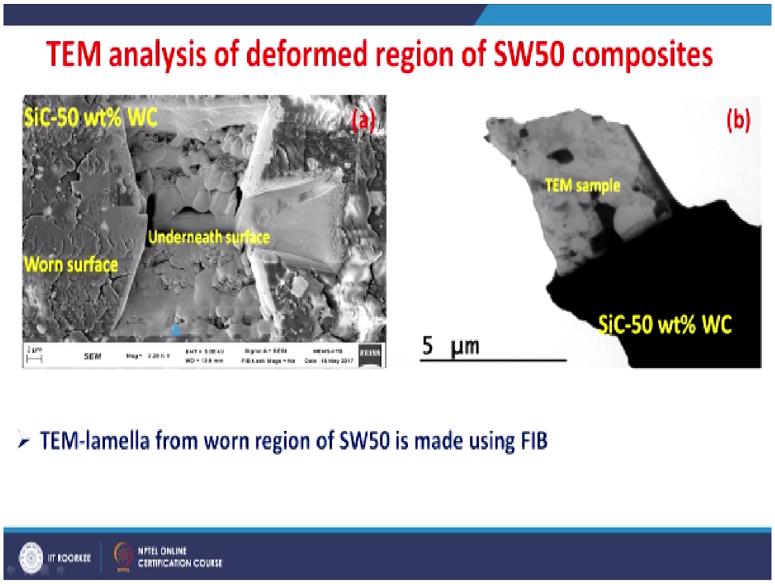

To understand the origin of such behavior the TM analysis was done on the deformed region of the selected composite. A TEM lamella was made from the worn region using the FIB. So this TEM sample was subjected to further investigation.

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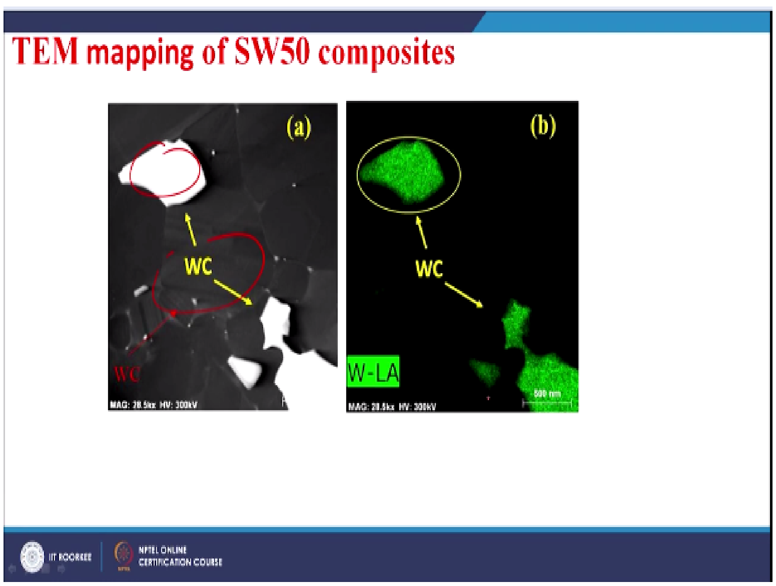

So this shows the silicon carbide grains and then tungsten carbide particles. Tungsten carbide particles.

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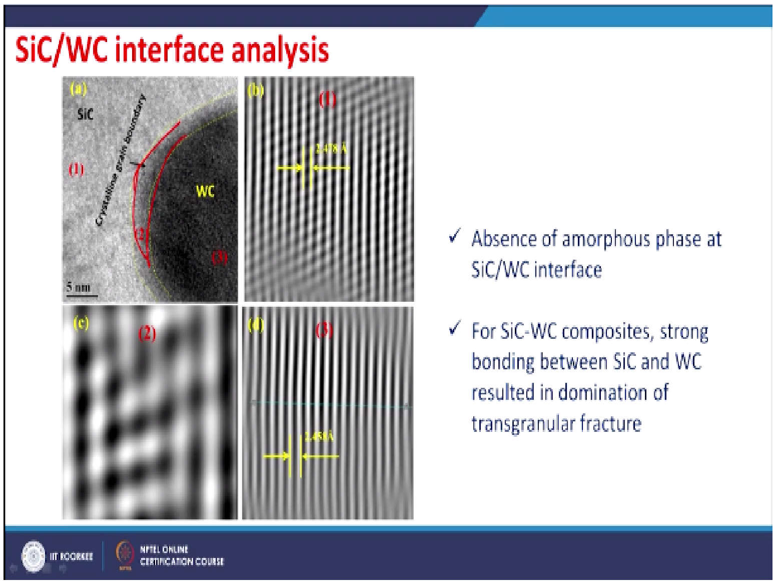

And the high resolution TEM analysis show the interface does not have any amorphous region. So they tungsten carbide as well as the silicon carbide grains are very strongly bonded. So this strong bonding resulted in the damnation of transgranular fracture which we already saw fractured surfaces of this composite. The intragranular fracture mode was dominant when there was no tungsten carbide particle. In case of composite having a tungsten carbide particles you have dominantly transgranular fracture.

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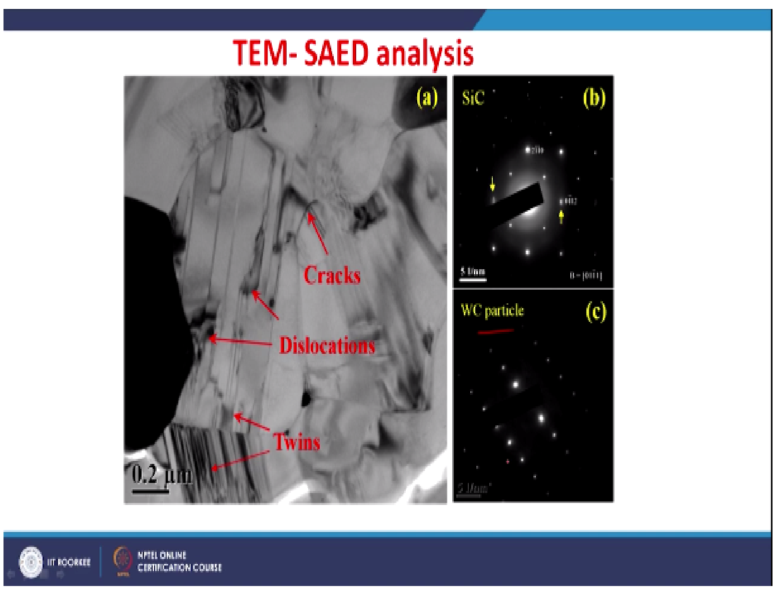

Further, the selected area diffraction analysis also indicate the crystalline arrangement of this silicon carbide or this tungsten carbide particles. In addition to that, these worn regions the regions underneath the worn surfaces they show the signatures of these cracks as well as the dislocations. In addition to these dislocations and cracks we can also see lot of twins. The SAED pattern also indicate the presence of the twin.

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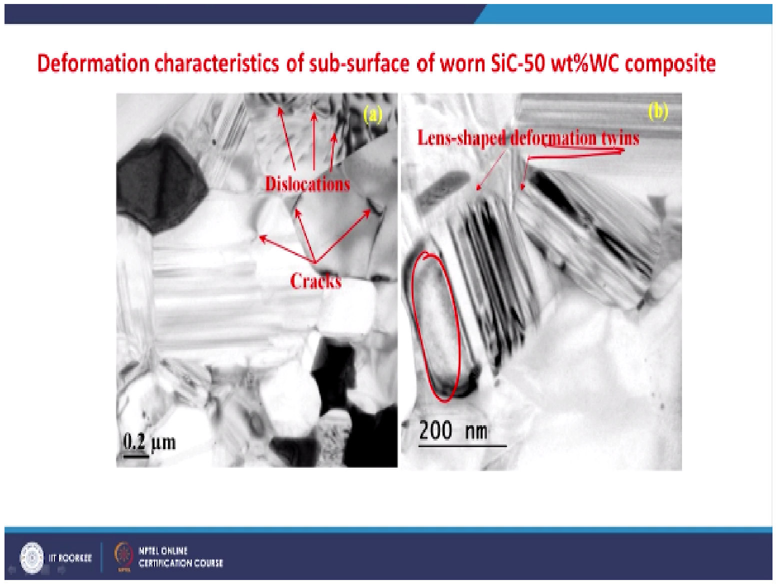

So the deformation is possible just below this worn region in terms of the dislocations as well as the twins. As we know the silicon carbide ceramics have very less number of sleep systems it is quite possible the deformation exists happen by the formation of these twins. The shape of this twins indicates the lens which indicate the deformation resulted, deformation induced twins. S can you see the grains on the silicon carbide, the cracks and the dislocations are present whereas the dislocations do not present in the tungsten carbide or the interface; of this tungsten carbide or silicon carbide.

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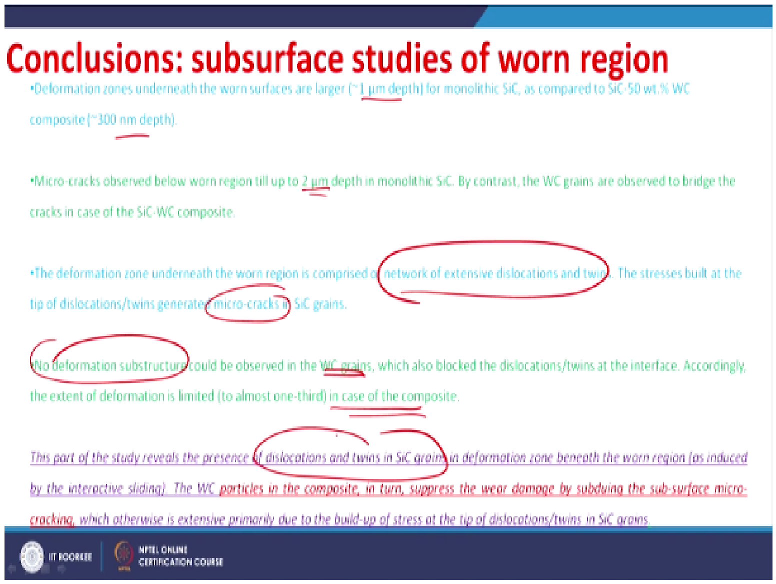

So computing the subsurface study results, the deformation zones underneath the worn surface are larger for monolithic silicon carbide as compare do silicon carbide tungsten carbide composite. There are more or less three times more for the silicon carbide ceramics as compare to silicon carbide 50% tungsten carbide composite. Microcracks are observed below the worn region till 2 micron meter depth for monolithic silicon carbide ceramics.

By contrast the tungsten carbide grains are observed to bridge the cracks in case of silicon carbide tungsten carbide composite. The deformation zone underneath the worn region is compressed of network of extensive dislocations and twins. So the stresses built at the tips of these dislocations and twins generate the microcracks so you see lot of microcracks so, in silicon carbide grains.

Whereas no deformation substructure is observed in the tungsten carbide grains which also blocked the dislocation or twins at the interface therefore, the extents of deformation is limited to almost 1/3rd what we observed here in case of the composite. So this particular study is very important in the sense that preparation of sample for TEM analysis, the sample must be taken from the region underneath the worn surface.

So for that FIB was use. And the TEM analysis was done carefully which revealed these information about the deformation zones the cracking as well as the beneficial effect of the tungsten carbide particles and the silicon carbide ceramics. So the particular study reveals the presence of dislocations or twins in the silicon carbide grains in deformation zone beneath the worn region.

The tungsten carbide particles in the composites in turns suppress the wear damage by subduing the subsurface micro-cracking. So which otherwise is found to be very extensive mainly because of the built up of stresses or the tips of this dislocations or twins in the silicon carbide grains. So these stresses were developed because f the interactive sliding. So the sliding induced stresses, a responsible for the cracking.

The cracking can be minimized when you use the tungsten carbide particles that mean a composite approach is very, very much beneficial in suppressing the wear damage by subduing the subsurface micro-cracking. Let us go to the last part of the; this lecture.

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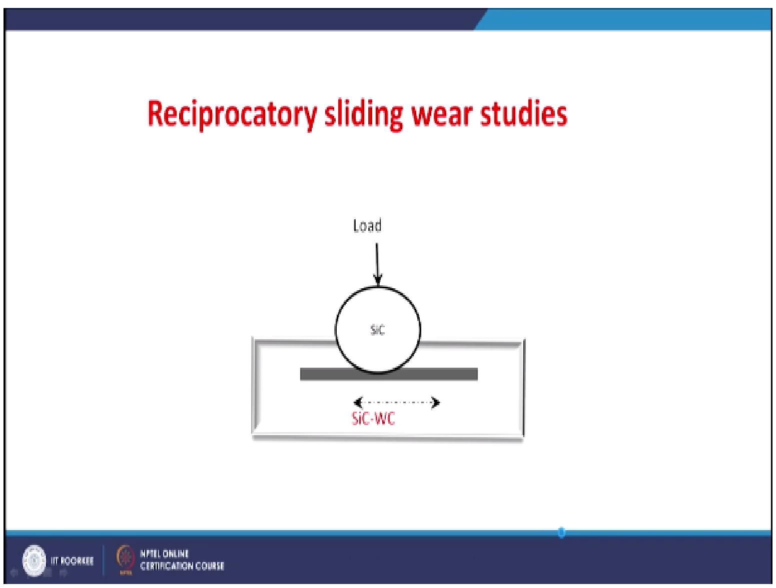

The Reciprocatory sliding wear studies.

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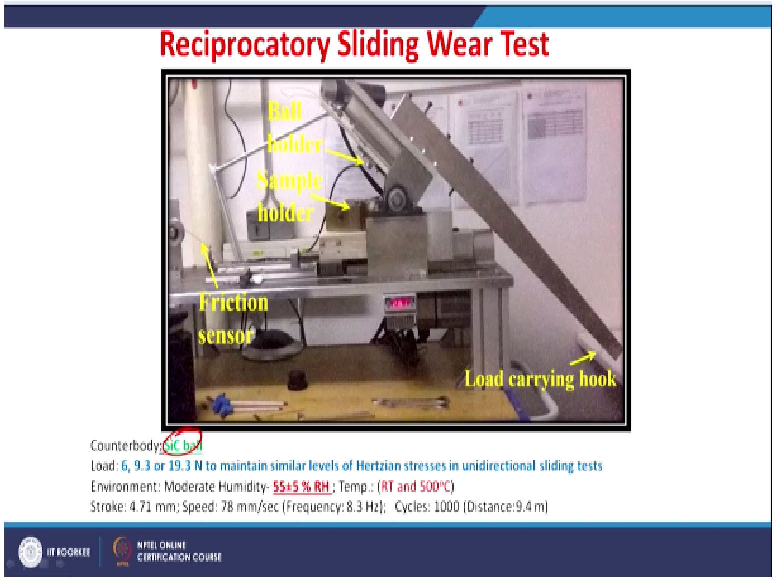

In order to understand the effect of the sliding mode from unidirectional to a reciprocatory We used reciprocatory sliding wear test operators where the ball was used as silicon carbide only and the load we changed from 6 to 9 Newton. These loads were selected to maintain the similar levels of Hertzain stresses which were used in the unidirectional sliding test. So these were done in the moderate humid condition at two different temperatures the room temperature and ironed Celsius.

So the major of the study is to understand the effect of the tungsten carbide content as well as the temperature of the testing on the reciproacatory sliding wear behavior of the silicon carbide tungsten carbide composites.

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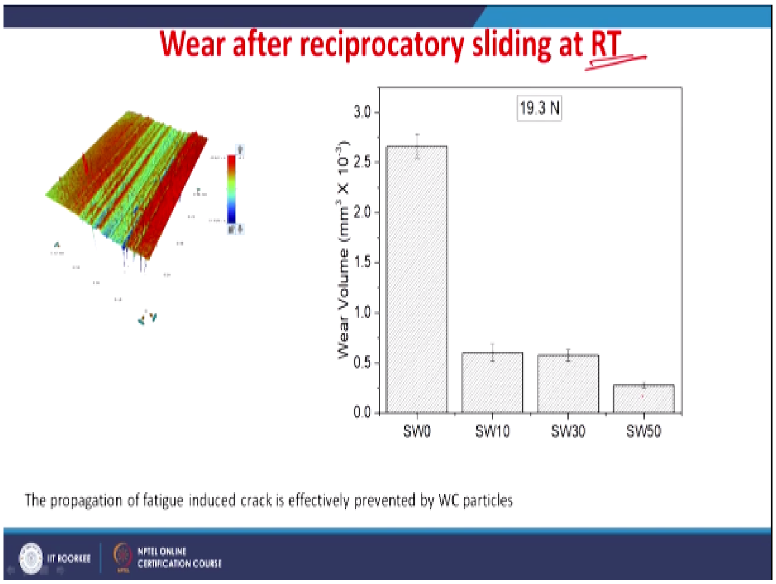

Now you see the volume of the composites one at room temperature. So as the tungsten carbide is introduced in the silicon carbide ceramics the wear was substantially decreased, that means the reciprocatory sliding which induces the fatigue induced cracks, those are effectively prevented by the tungsten carbide particles. This study actually was selected to understand the behavior of this composites in a reciprocatory sliding. In reciprocatory sliding we have a difference in the content time of this debris so it will actually affect the properties or the performance.

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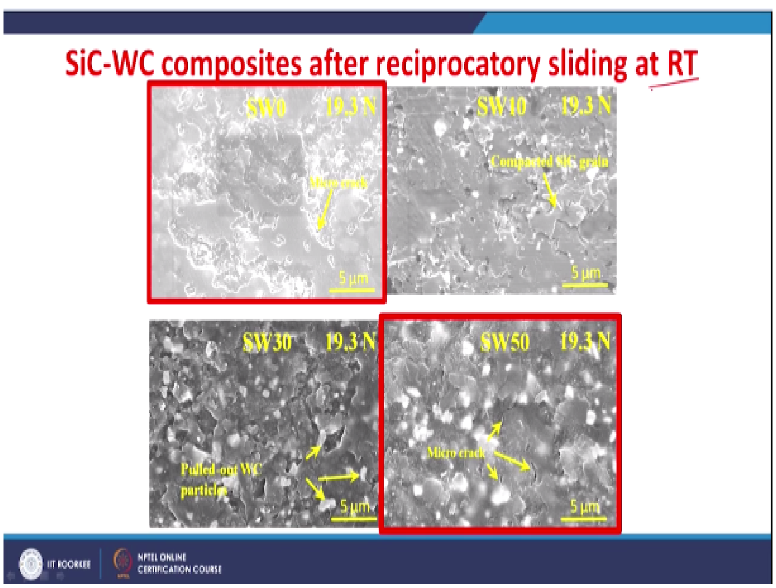

So if you can see the silicon carbide tungsten carbide composites after sliding in a reciprocatory mode at room temperature the surfaces were showing the micro-cracks and then this pull-out of this tungsten carbide particles, but with increase in the tungsten carbide content actually the fracture was minimum, reduced.

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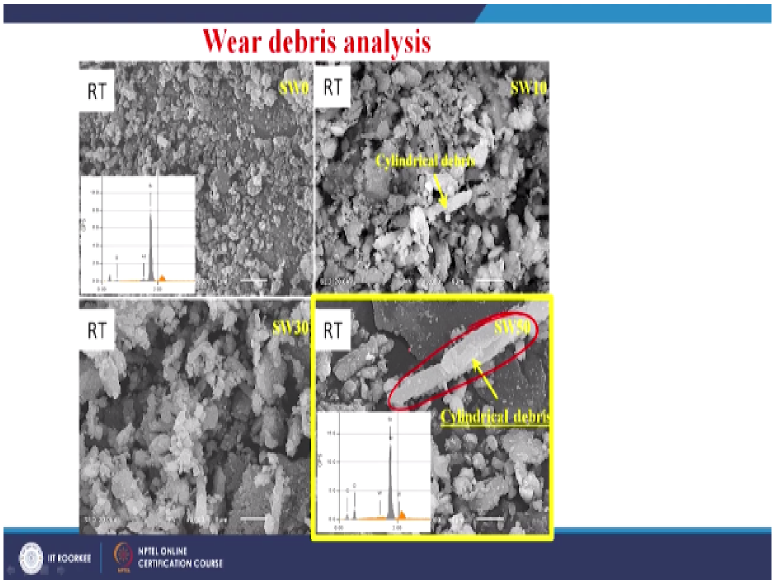

The debris analysis particularly show the presence of the cylindrical shaped debris. So the (()) (35:20) shows these are oxides of the silicon, so you can see this as they tungsten carbide content increased you get more and more finer debris and then as well the presence of the cylindrical shaped debris.

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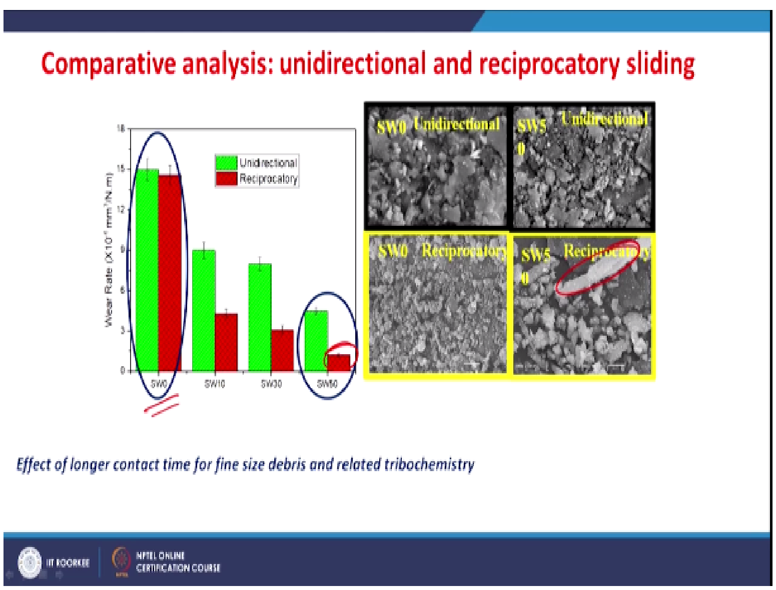

So this information is very important to analyze the unidirectional reciprocatory sliding wear test result. You can see in case of silicon carbide ceramics without having tungsten carbide the wear rate was more or less same either it is unidirectional reciprocatory. Because; and as the tungsten carbide content is increased you get a reduction in the wear rate in the reciprocatory sliding, reciprocatory sliding wear test.

That indicates the effect of the longer content time for the finer debris particle, so these finer size debris will connect each other and then tend to form a cylindrical debris. The cylindrical debris generally facilitated sees in sliding and the cylindrical debris generally forms only when there is a viscous surface. This viscous surface is like the viscous surface layer is because of the interaction with the silicon oxide present on the silicon carbide particles are present due to these wear test.

So this silicon oxide reacts with the moisture and then forms a silicon oxyhydrate. The silicon oxyhydrate being these particles they collect each other and then forma cylindrical debris from the; so the viscous surface is removed from the composite and then the debris are connected to each other and then form cylindrical shape. So there is a Tribo-chemistry when the sliding test mode was changed from unidirectional to reciproactory. In unidirectional it is a mechanical fracture only whereas in reciprocatory there is a signature the tribo-chemistry involved in that.

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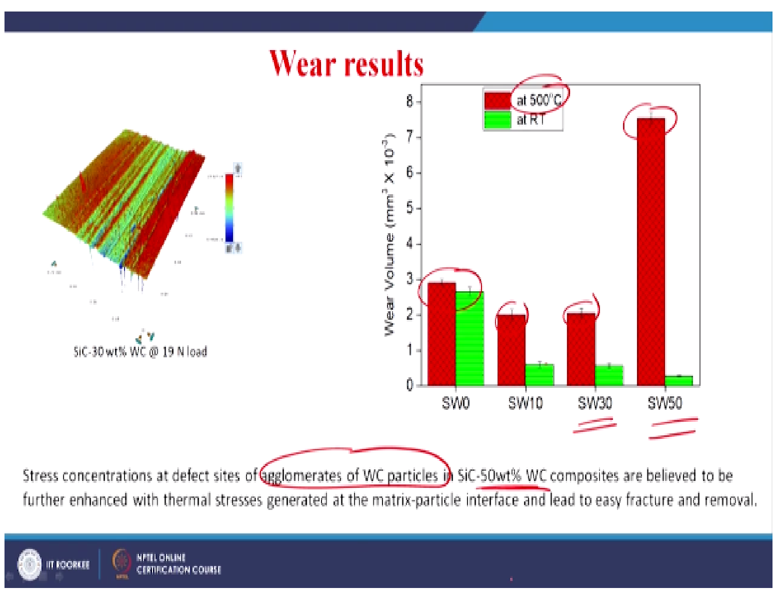

So if you look at the wear results obtained for this composites tested in unidirectional reciprocatory sliding conditions. So the effect of the longer content time for the finer sized debris that lead to this tribo-chemistry and the resultant wear, so you get a decrease in the wear. When comparing the results obtained in the reciprocatory sliding conditions at different temperatures of room temperature 500 degrees Celsius.

You can see that silicon carbide tungsten carbide composites always show higher wear when worn in the high elevated temperatures compare to those at the room temperature. In silicon carbide ceramics the difference is very much less. So it is believed that stress concentration at the defect sites those are attributed for the increased wear.

Also, at the higher temperatures the materials often though the strength is is reduced so you get a more amount of material removed from the surface. But if you look at the SW30 and SW50 the stress concentrations at the defect sites of agglomerates of tungsten carbide particles which we saw in the previous slide. Agglomerates are dominantly present in the, in the composite with a larger amount of tungsten carbide content.

So these agglomerates result into increased stress concentrations so the stress concentrations at the defect sites of this agglomerates of tungsten carbide particles particularly in SW50 composite are believed to be further enhanced with thermal stresses generated at the interface of these matrix and particle so that leads to easy removal of the material. So you get a very larger wear volume when a tungsten carbide was around 50%.

The silicon carbide tungsten carbide composites surfaces after reciproactory sliding a room temperature and high temperature of 500 Celsius. You can see there is a difference in the mechanism. The fracture is increased when the testing was done at higher temperatures, the fracture is increased. So at a room temperature as the tungsten carbide content is increased we can see certain tribochemical layer formations and the removal whereas such a tribochemical layer formations are not found in case of those composites worn at high temperatures.

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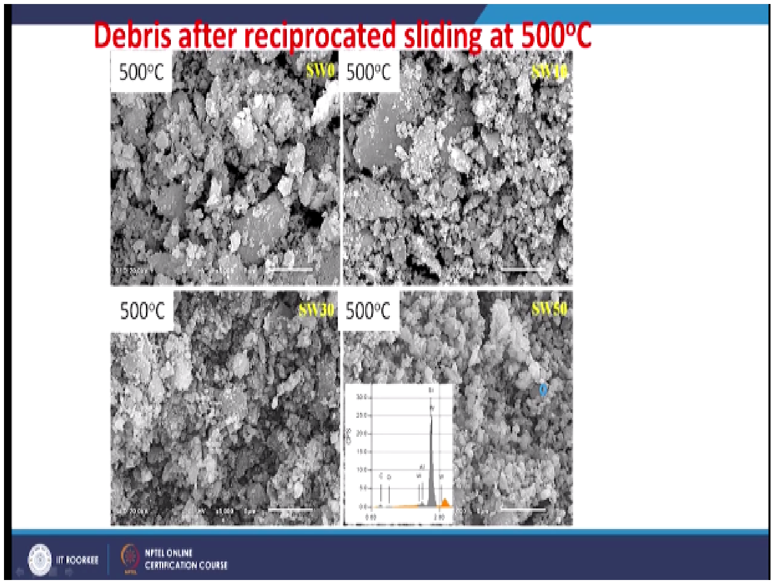

So the debris also show there is no presence of any cylindrical shaped debris. So these are all fractured grains and no signatures of any tribo-chemistry.

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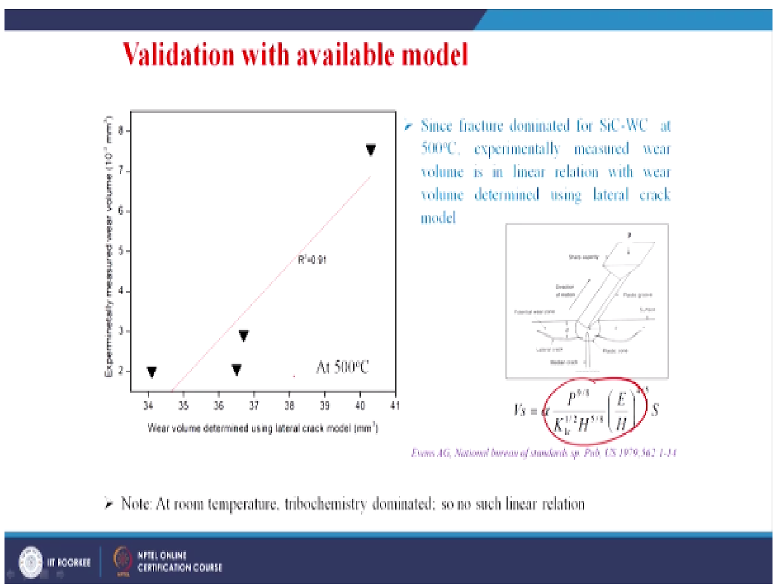

We also validated the experimentally measured wear volume with the wear volume determined using the lateral crack model. So since fractured dominated for the silicon carbide tungsten carbide at higher temperatures, so experimentally measured wear volume is an linear relation with the wear volume determined using the lateral crack model. But at room temperature because the tribo-chemistry was dominated no such linear relation is observed. So this also indicates the mechanical fracture at higher temperature whereas tribochemical wear at lower temperature, room temperatures.

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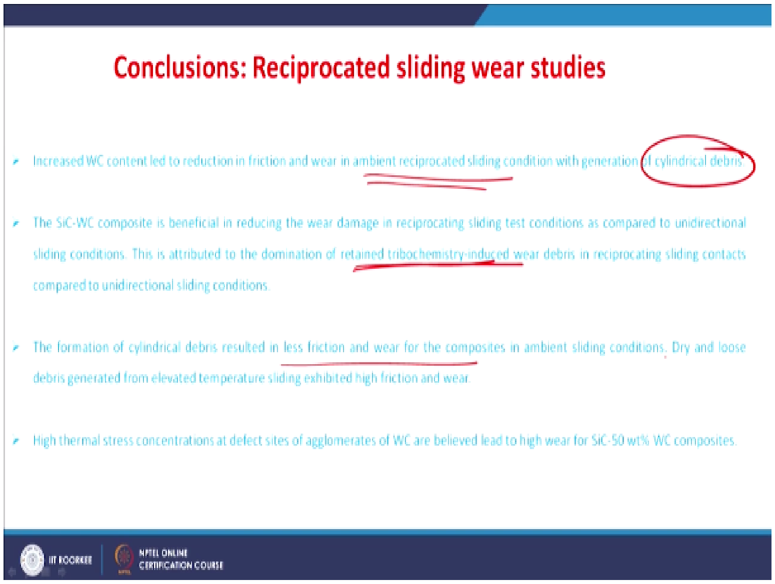

Concluding these results from the reciprocated sliding wear studies. Increased tungsten carbide content resulted in reduction in friction and wear in ambient reciprocated sliding conditions with the generation of cylindrical debris. So cylindrical debris formation is observed only in the ambient conditions. The silicon carbide tungsten carbide composite is beneficial in reducing the wear damage in reciprocated sliding test conditions as compared to the unidirectional sliding test conditions.

This particular observation is attributed to the domination of retained tribo-chemistry induced wear debris. Because of the longer time for the debris in the content so the tribo-chemistry induced wear is much retained. So in the reciprocated sliding conditions, so it is much beneficial. The formation of cylindrical debris resulted in lesser friction and the wear for the composites in the ambient sliding conditions. Whereas dry an loose debris generated from the elevated temperature sliding conditions that resulted in the high friction and the wear.

So high thermal stress concentration at the defect sides of the agglomerates of tungsten carbide particles are believed to lead to higher wear when there is a larger amount of tungsten carbide content. So this particular study indicates the influence of the sliding mode, the influence of the tungsten carbide content in the silicon carbide tungsten carbide composite and the influence of the temperature.

When the sliding mode was changed the reciprocated sliding actually gave more tribo-chemistry induced wear. And the cylindrical debris were obtained in the ambient shaped reciprocated sliding condition and that resulted in the less friction and the wear. Whereas dominantly mechanical fracture is observed in those reciprocated sliding wear test done at elevated temperature so the higher friction and wear was observed.

With respect to tungsten carbide content always the silicon carbide tungsten carbide composite it is beneficial in reducing the wear damage in reciprocated sliding conditions. As the fatigue induced crack is deflected or bridged so the removal of the material by fracture is reduced so you got a benefit in the silicon carbide tungsten carbide composite. So finally summarizing, we have gone through the seven results obtained in the tribological study at different length scales for the silicon carbide tungsten composites.

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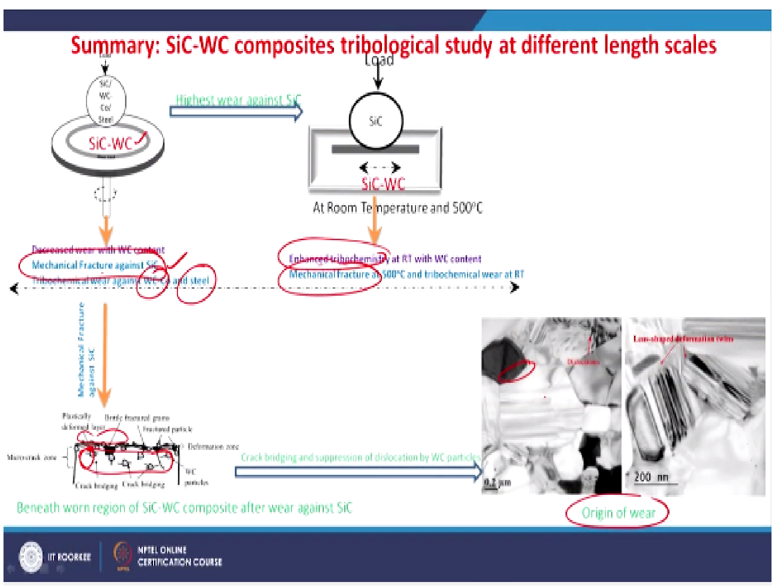

So we form; wear was decreased when tungsten carbide content is increased in a unidirectional sliding conditions as well as the reciprocated sliding conditions, whereas mechanical fractures against to silicon carbide ceramic ball in a unidirectional sliding condition, tribochemical wear dominates against a tungsten carbide cobalt or the steel ball.

So in case of reciprocated sliding conditions which were done in silicon carbide against silicon carbide ball only. So they again showed enhanced tribochemistry. So you can see the mechanical fracture against to silicon carbide in a unidirectional conditions, they actually changed to tribochemical induced wear at room temperature for this composites. Whereas at higher temperatures, again the mechanical fracture is dominant.

So in order to understand the origin of material removal we selected a composite silicon carbide tungsten carbide composite for the study subsurface regions. We selected the composites worn against the silicon carbide only. The region again because it is only the mechanical fracture, there is no tribochemical layer, so it is easy to understand the origin of the material removal from the beneath the region, worn region.

So subsurface regions, subsurface study indicate the plastically deformed region as well as the cracked region. And presence of the tungsten carbide always is beneficial in reducing the wear by crack bridging and crack deflection, so that the fracture is reduced, wear is reduced. So beneath the worn region the silicon carbide tungsten carbide composite show lesser propagation or reduced propagation of the cracks because of the tungsten carbide particles present.

Further analysis by TEM shows the major, the origin of the wear, the wear occurs by the cracking. The cracking is possible by the stresses induced at the, induced by the sliding at the tips of those deformation signatures like dislocations or the twins. So these cracks will propagate further and lead to material removal.

When a tungsten carbide particle is present at the interface all these cracks are actually stopped. Or the deformation signatures are not present at the interface are inside the tungsten carbide particles. So this particular study is taken to understand the tribological behavior or these composites at different length scales either from the worn surface to underneath the worn surface. Particularly, underneath worn surface the study was done to identify the origin of the wear. So thank you. We will continue this in the next lecture.