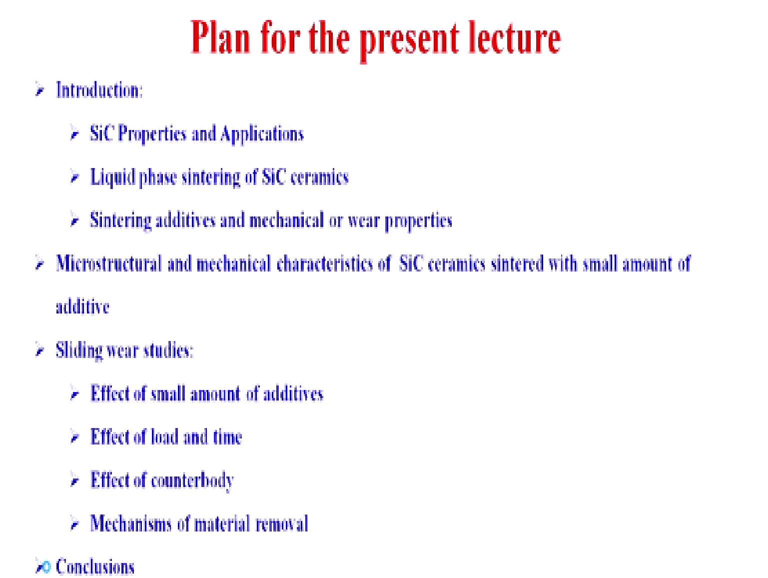
Friction and Wear of Materials: Principles and Case Studies
Prof. B. Venkata Manoj Kumar
Department of Metallurgical and Materials Engineering
Indian Institute of Technology – Roorkee

Lecture - 19
Sliding Wear of SiC Ceramics

Welcome all to the NPTEL course Friction and Wear of Materials Principles and Case Studies. So I am B. Venkata Manoj Kumar from IIT Roorkee. So in this course the present lecture will cover the sliding wear behavior of silicon carbide ceramics.

(Refer Slide Time: 00:45)



So the plan for the present lecture is first I will introduce the silicon carbide ceramics properties and their typical applications and liquid phase sintering of silicon carbide ceramics. Sintering additives and their effect on mechanical and wear properties and after this introduction I will show you the microstructural mechanical characteristics of silicon carbide ceramics sintered with very small amount of additive.

This will be followed by the (()) (01:19) results from the sliding wear behavior particularly on the effect of small amount of additives, effect of load and time of the sliding test. Effect of counterbody used in the sliding test and the mechanisms of material removal and then this will be followed by conclusions from the present study.

(Refer Slide Time: 01:43)

Silicon Carbide (SiC) Ceramics

SiC ceramics exhibit promising tribological behaviour and preferable for structural applications due to its superior properties such as:

- High hardness (22-28 GPa)
- Moderate fracture toughness (3- 4.5 MPa.$m^{1/2}$)
- Excellent high temperature strength (up to 1200°C)
- Low thermal expansion and high thermal conductivity
- Low friction, and superior resistance to wear and corrosion

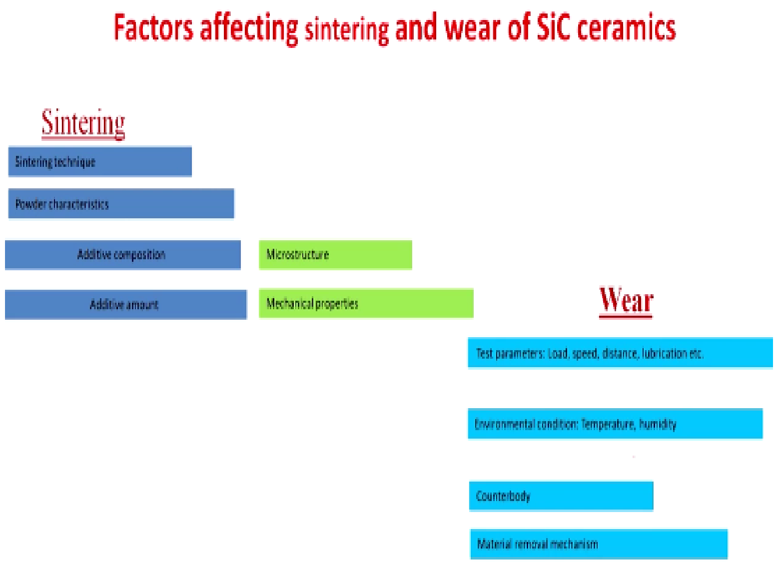
So first the silicon carbide ceramics they are very promising materials for tribological use because of their attractive properties such as high hardness it would be more than 22 gigapascal and the moderate fracture toughness 3 to 4.5 MPa root meter and it posses excellent high temperature strength that strength can be retained even up to 1200 Celsius and it has low thermal expansion and high thermal conductivity and it exhibits very less friction and superior resistance against wear or corrosion.

(Refer Slide Time: 02:28)

Typical engineering applications of SiC ceramics

So because of these combination of properties several engineering applications silicon carbide ceramics is much used for such as this ball bearings and then cutting tools and Armor applications and high temperature obligations and all these thing these applications require wear resistance.

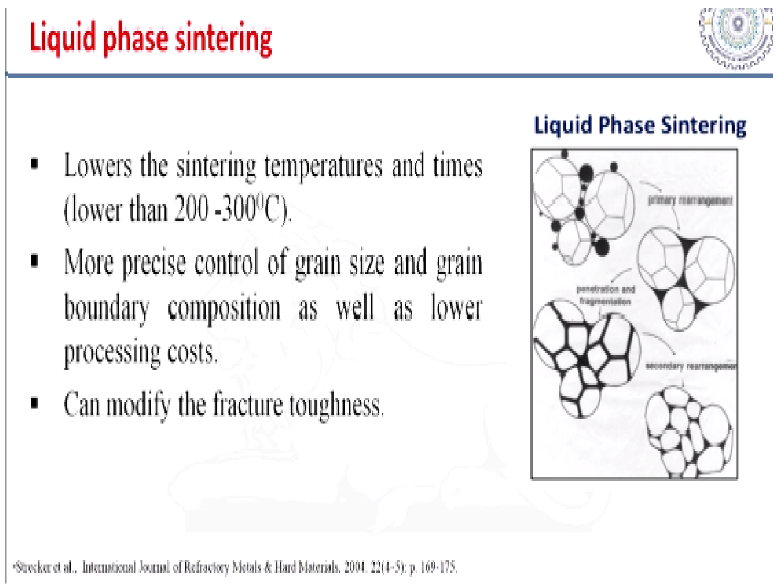
(Refer Slide Time: 02:58)



So if you look at the factors affecting both the sintering and as well as the wear of silicon carbide a sintering is affected by the technique you are using and the characteristics of the powders you are using for the sintering and importantly the composition and the content of additives you are using for the sintering of the silicon carbide. So these sintering factors will be influencing the microstructural features of the sintered materials and mechanical properties of the sintered materials.

So these in turn will affect the wear behavior of the silicon carbide ceramics particularly the factors for the wear behavior like load, speed, distance and lubrication and environmental conditions like temperature, humidity and the counterbody of the silicon carbide ceramics will affect the overall behavior.

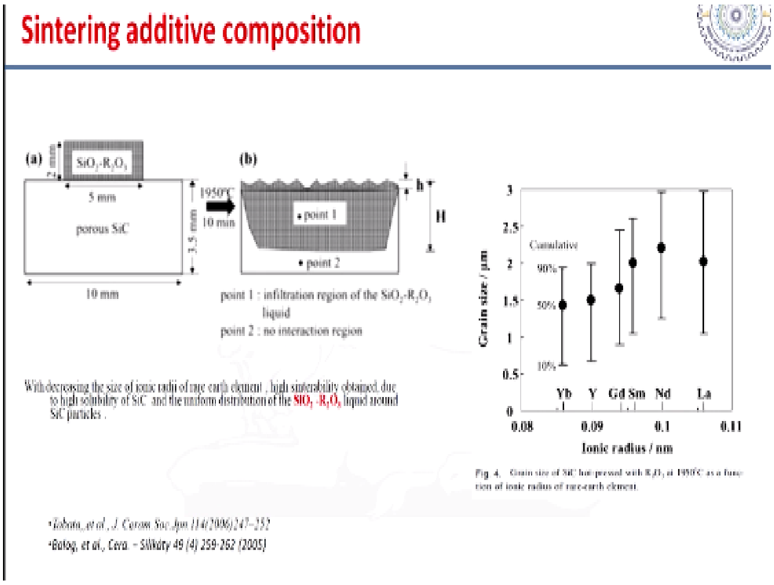
(Refer Slide Time: 04:02)



So if you look at this liquid phase sintering. A liquid phase is very beneficial because it lowers the sintering temperatures and also the time required for the sintering. It lowers the sintering temperature by around 200 to 300 Celsius then that is required for the conventional solid state sintering. It also gives more precise on the grain size control and also the grain boundary composition.

And it affects the processing cost and in turn the microstructure will result in a fracture toughness improvement. So the liquid phase sintering is generally used for sintering of silicon carbide ceramics.

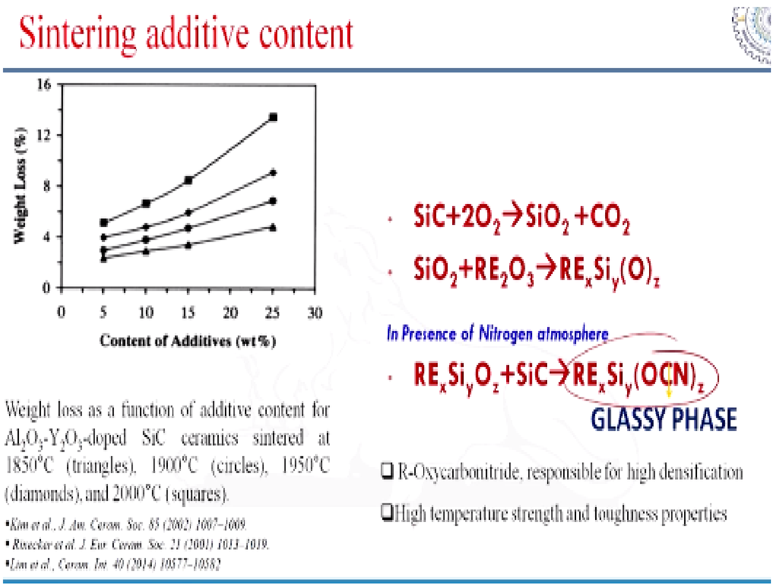
(Refer Slide Time: 04:55)



So in the liquid phase sintered silicon carbide ceramics the additive which is used for the sintering its content as well as the composition will influence the microstructure. So if you look at these data from the literature with decreasing the size of the ionic radii of rare earth element used for the sintering additives. The solubility of silicon carbide will be improved and you will have a uniform distribution of the liquid phase around the solid SiC particles so that results into high sinterability.

So in this example the silicon oxide and sometime rare earth oxides are used as a sintering additive. So if you see this one the grain size as a function of ionic radius as the ionic radius of the rare earth element used in this additive system of silicon carbide and rare earth oxide additives. So as the ionic radius decrease the grain size also decreased.

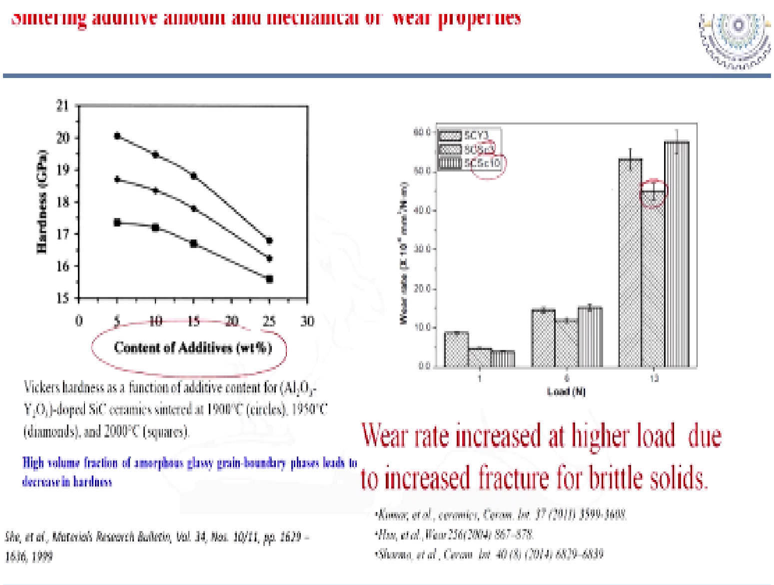
(Refer Slide Time: 06:02)



Regarding the additive content, the weight loss is shown as a function of additive content here in this particular slide. So you can see the as the content is decreased the weight loss is also decreased. Generally, the silicon carbide particles will have surface or rich with the silicon oxide and the silicon oxide reacts with the rare earth oxide from the additive system and at high temperature it forms a rare earth silicon oxide.

And in presence of nitrogen atmosphere these rare earth silicon oxide with the silicon carbide converts to a glassy rare earth silicon oxycarbonitride and this oxycarbonitride operated the silicon is responsible for improved densification in the liquid phase sintering of the ceramics. So because of that we get a high temperature strength and improved toughness.

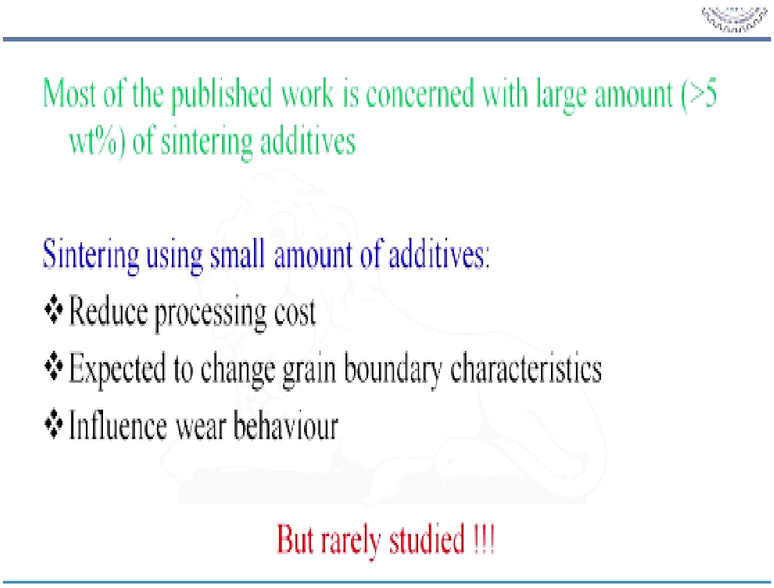
(Refer Slide Time: 07:06)



But if you look at this sintering additive affect on the mechanical and wear properties. So as the sintering additive content is decreased the hardness is improved and the wear rate also decreased with decrease in the content of this additives. In this example the silicon carbide sintered with yttria 3%, 3% Scandia and 10% Scandium oxide. So with the increase in the content of this additive system of this Scandia and then 3% Scandia and 10% Scandia.

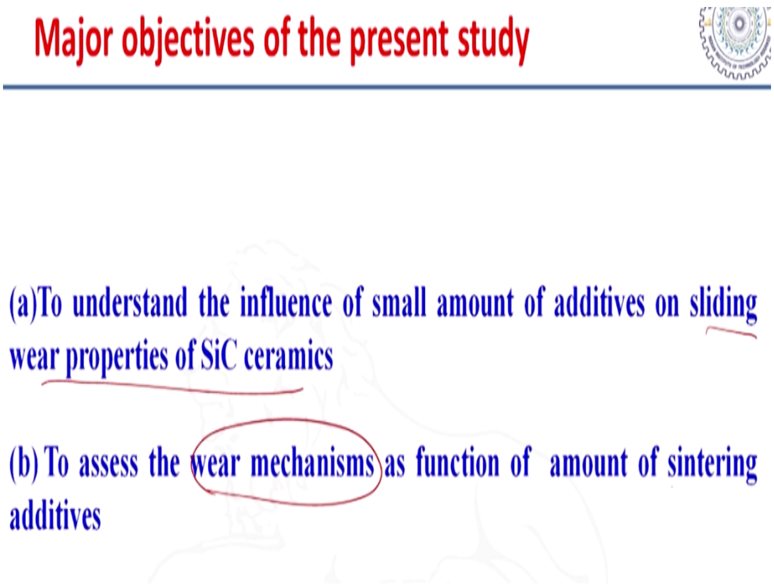
You can see the wear rate is actually decreased and with the wear rate also increased at higher load. Generally, it happens for the brittle materials because of the increased fracture. So the wear rate is increased at a higher load even at a higher load the silicon carbide ceramics sintered with a smaller amount of additive showed a less wear rate.

(Refer Slide Time: 08:17)



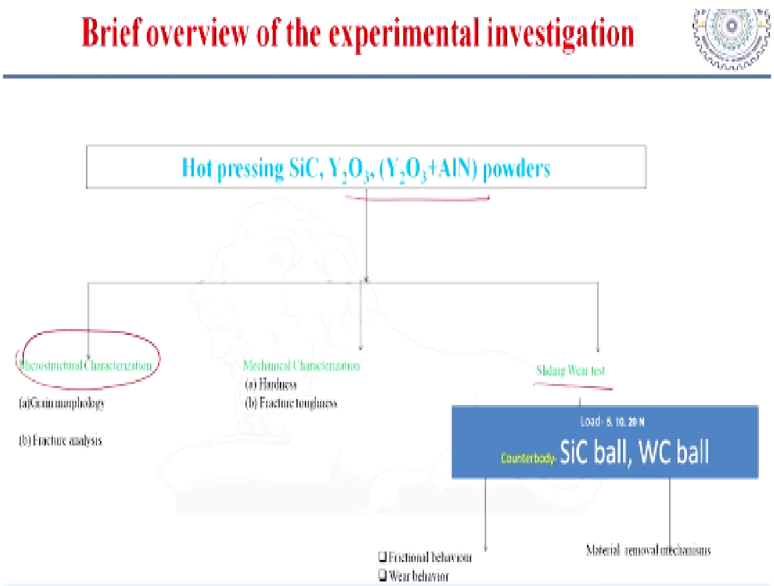
So the brief literature of this liquid phase sintered silicon carbon ceramics and their mechanical and wear studies indicate that sintering using small amount of additives reduces overall cost of the processing and also changes the grain boundary characteristics finally influencing the wear behavior, but a small amount of additive affect on this mechanical and wear behavior is not studied to a larger extent.

(Refer Slide Time: 08:54)



So in this context the objectives of the present study are like this to understand the influence of small amount of additives on the sliding wear properties of the silicon carbide ceramics and to assess the dominant wear mechanism as a function of the amount of sintering additives.

(Refer Slide Time: 09:17)



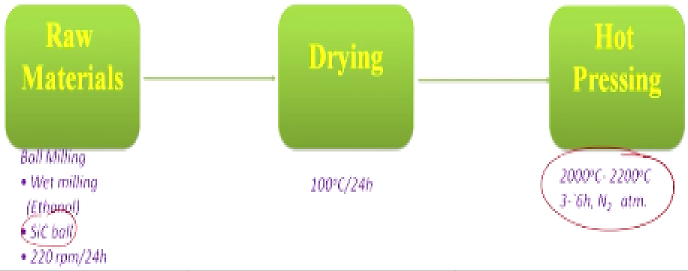
So this is the overall view of this experimental investigation where the silicon carbide ceramics with certain additive systems like Yttrium oxide and a mixture of Yttrium oxide and aluminum nitride after hot pressing those are subjected to micro structural studies to understand the grain morphology and also the analysis of the fracture surfaces. This is followed by mechanical property study particularly the hardness and fracture toughness.

And the performance of these sintered materials will be studied in a sliding wear conditions at a different loads and the frictional wear behavior will be particularly studied and focusing on the material removal mechanisms.

(Refer Slide Time: 10:08)

Fabrication of SiC Ceramics

(prepared at University of Seoul; Courtesy Prof. Young-Wook Kim)



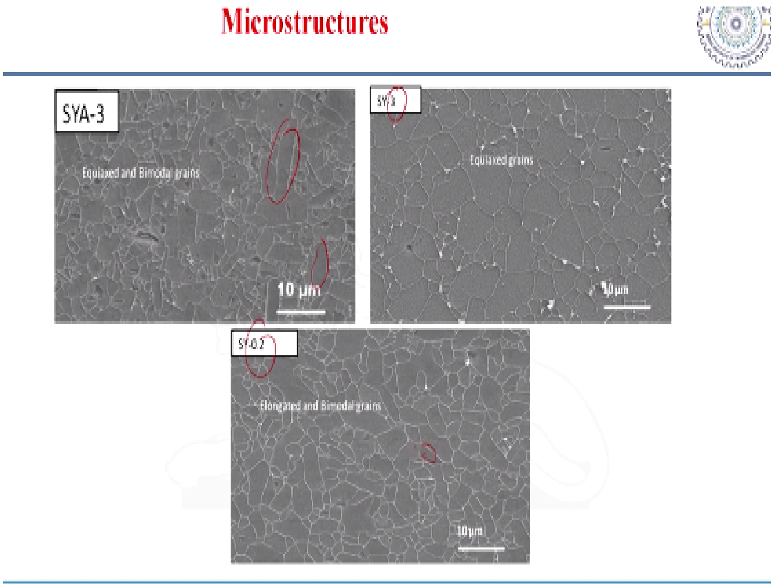
Sample designation	Batch composition (wt%)	Sintered density (g/cc) (Relative density (%))
SYA-3	97 β-SiC+1.262 AlN+1.738 Y_2O_3	3.24 (98.0)
SY-3	97β-SiC+3Y_2O_3	3.16 (97.4)
SY-0.2	99.8β-SiC+0.2Y_2O_3	3.21 (99.9)

The fabrication of these particular silicon carbide ceramic system was done at the University of Seoul with the help from the Professor Young Wook Kim of University of Seoul and these silicon carbide ceramics powders of silicon carbide this additives aluminum nitride Yttrium oxide and only Yttrium oxide. So these respective batches were mixed in a ball mill using a silicon carbide ball and this in a wet milling medium of ethanol.

They are dried and then hot pressed in a temperature range of 2000 to 2200 Celsius for 3 to 6 hours in nitrogen atmosphere and then this resulted into a decent density of the sintered material. So in this particular study 3 different samples were used these are the batch composition beta silicon carbide with aluminum nitride and Yttrium oxide the sum of these additive system additives of aluminum nitride and Yttrium oxide 3 weight %.

And the same 3 weight % of only Yttrium oxide is used in the next batch and then very smaller amount of Yttrium oxide is used in the other batch. So 3 batches were prepared the samples are designated as SYA-3 SY-3 and SY-0.2.

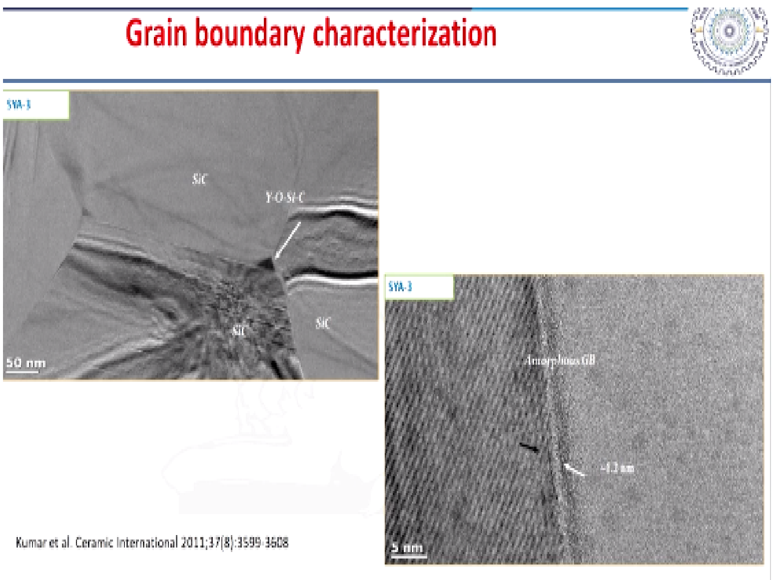
(Refer Slide Time: 11:42)



So the sintered carbon ceramics shows the microstructure and SYA-3 where the silicon carbide ceramics sintered with 3 weight% of aluminum nitride and Yttrium oxide mixture showed overall equiaxed grains, but with sometime bimodal grains as well where a 3% Yttrium oxide was only used as an additive. It showed only equiaxed grains, but when the sintering additive content is decreased from 3% to 0.2%.

You can see there are elongated grains as well as the bimodal grains. So it shows with change in the additive content as well as additive composition there is a variation in the microstructures.

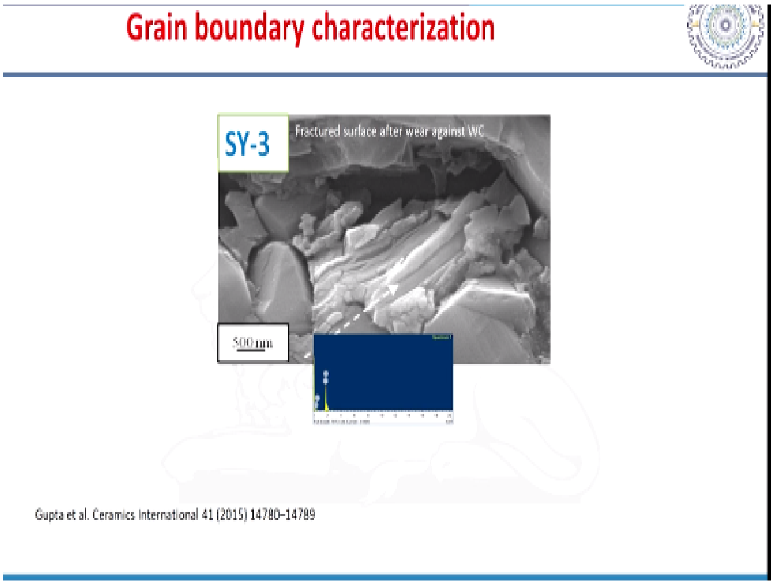
(Refer Slide Time: 12:39)



A systematic (()) (12:40) analysis of the sintered material show a grain boundary characterization also changed. So the silicon carbide ceramic edited sintered with a 3%

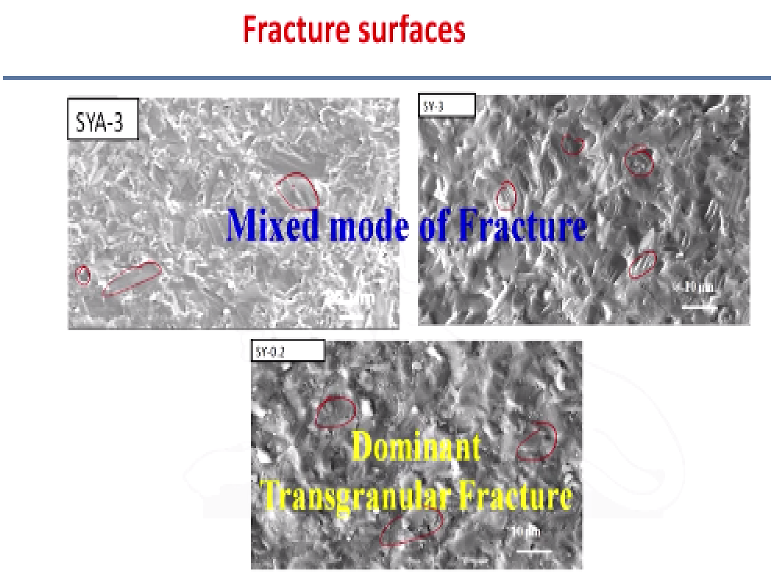
Yttrium oxide and aluminum nitride shows these glassy boundaries these glassy phase existing in the triple point junctions as well as the grain boundaries. You can see the high resolution (()) (13:09) images also showing the amorphous grain boundary of around 1 nanometer.

(Refer Slide Time: 13:16)



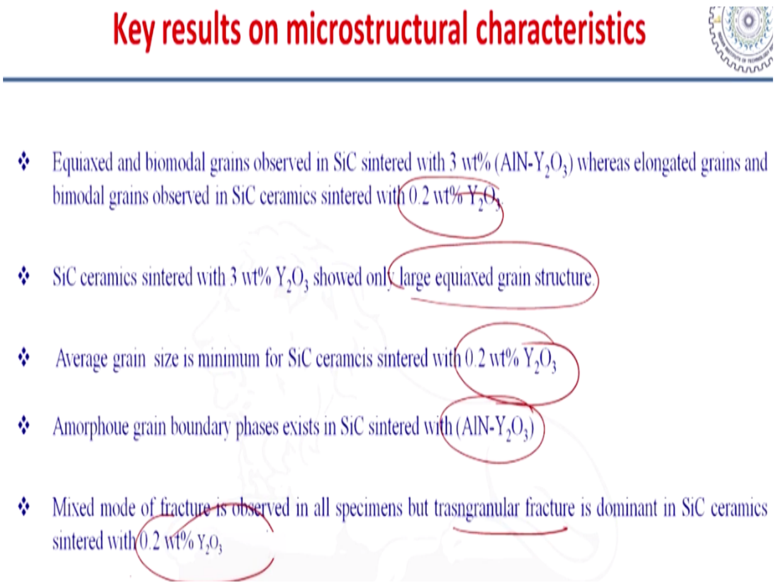
Whereas only 3% of Yttrium oxide is just the particular fractured surface after the wear shows the fracture of these Yttrium oxide phase.

(Refer Slide Time: 13:29)



The overall fracture morphology is a mixed mode of fracture which shows all the intergranular as well as the transgranular mode of fracture, but as the sintering additive it decreased from 3 to 0.2%. You can see dominantly transgranular fracture. The intergranular fracture is significantly reduced. So with change in the additive content from 3 to 0.2% there is a change in the fracture morphology from intergranular and transgranular fracture as well as to the dominantly transgranular fracture.

(Refer Slide Time: 14:13)



So let us summarize the results on the micro structural characteristics of the sintered silicon carbide ceramics. We found equiaxed run bimodal grains in silicon carbide sintered with 3 %age of aluminum nitride and Yttrium oxide whereas elongated grains and bimodal grains are observed in the ceramics sintered with very small amount of 0.2% Yttrium oxide. Silicon carbide ceramics sintered with 3% Yttrium oxide showed only large equiaxed grain structure.

The average grain size is minimum for the ceramics sintered with smaller amount of Yttrium oxide and also (()) (14:56) analysis shows the amorphous grain boundary phase existing in those ceramics processed with aluminum nitride and Yttrium oxide additives and fracture surface analysis shows the mixed mode of fracture in all specimens, but dominantly transgranular fracture is observed in the ceramic sintered with a smaller amount of additives.

(Refer Slide Time: 15:24)

Mechanical Properties

Sample	Vickers Hardness (GPa)	Fracture Toughness ($Mpa.m^{1/2}$)	Flexural Strength (MPa)
SYA-3	21.4 ±3.3	4.1 ±1.3	--
SY-3	26.1±0.5	4.3 ±0.3	542.2 ±12.6
SY0.2	27.5±0.5	4.0 ±0.1	561.2 ±93.3

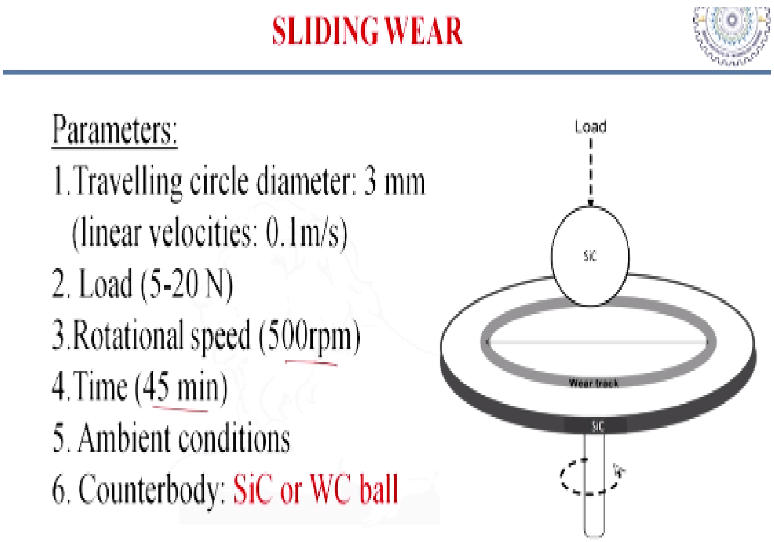
- Hardness and strength increased with decrease in amount of Y_2O_3 additive content.
- Amorphous second phase in SYA-3 is responsible for less hardness

Let us see the resultant mechanical properties of these ceramics. The Vickers hardness ranged between 21 to 27 gigapascal for this investigated ceramics whereas the fracture toughness is changed only from 4.1 to 4.3 MPa root meter. The flexural strength also changed having a higher strength observed in the ceramics sintered with the small amount of additive content. The small amount of additive content showed also higher hardness.

But the fracture toughness is more or less same. The hardness and strength increased with decrease in amount of Yttrium oxide additive content and amorphous phase found in the (()) (16:23) analysis in the silicon carbide ceramics sintered with Yttrium oxide and aluminum nitride is responsible for lesser hardness. So the first point from here is with additive content decrease there is a increase in the hardness as well as the strength.

But the hardness is found less for the ceramics sintered with aluminum nitride Yttrium oxide because of the amorphous second phase present along the grain boundaries. Let us understand the effect of this microstructural and mechanical characteristics on the performance when these ceramics are subjected to sliding wear.

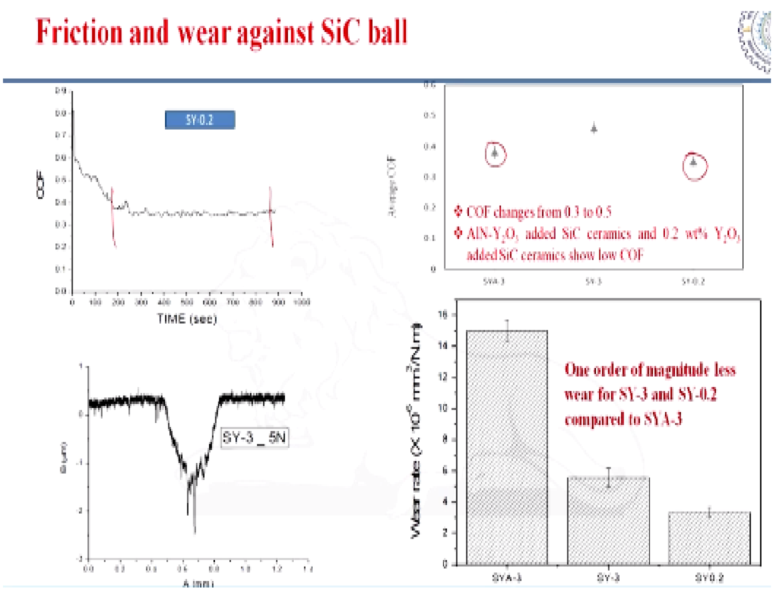
(Refer Slide Time: 17:17)



So the sliding wear test was done using a ball on disc sliding wear test apparatus. The ball was 3 mm diameter which is a commercially available ball and the disc of this investigated silicon carbide ceramics were rotated at a particular speed of 500 RMP for 45 minutes in ambient conditions against the silicon carbide ball as well as the Tungsten carbide ball. So both balls are of commercially available balls of silicon carbide or Tungsten carbide.

So first of all let us understand the behavior against the silicon carbide ball. The sliding wear behavior is understood with respect to the coefficient of friction and wear rate.

(Refer Slide Time: 18:15)

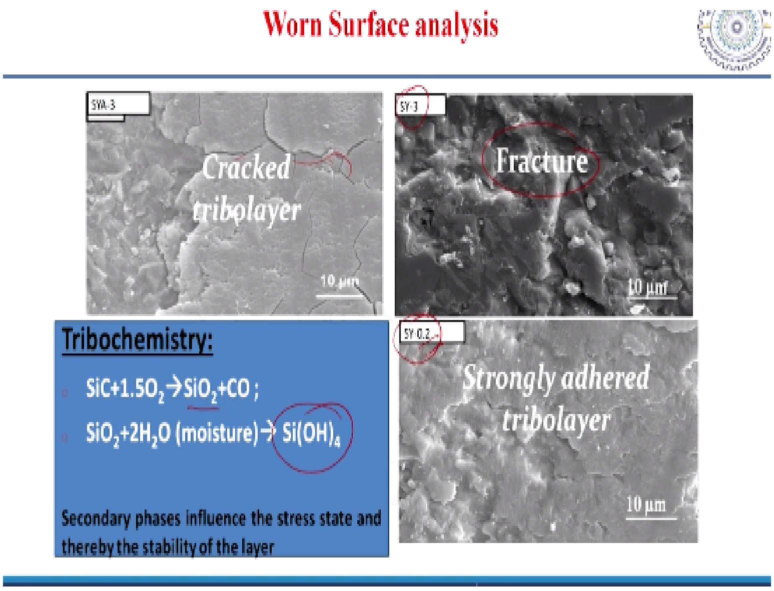


The coefficient of friction changes in a steady state from 0.3 to 0.5 with change in composition or the additive content. Aluminum nitride, Yttrium oxide added silicon carbide ceramics and 0.2 weight % Yttrium oxide added silicon carbide ceramics showed a lower coefficient of friction than the other one. The wear profile was studied using a profilometer and the depth and the wear were measured.

And then integrated over the distance it travelled. So you get a volumetric wear this is normalized by the load and the sliding distance to give a wear rate. So if you look at the wear rate variation with the additive composition as well as additive content. You can see almost one order of magnitude lesser wear for the silicon carbide ceramics sintered with Yttrium oxide additive compared with this aluminum nitride and Yttrium oxide additive.

And also we can observe a decrease in wear rate for the ceramic sintered with the very small amount of Yttrium oxide additive.

(Refer Slide Time: 19:34)



To understand the wear behavior it is necessary to study the worn surfaces. The worn surfaces was studied using a (()) (19:44) analysis which shows the silicon carbide ceramics sintered with aluminum nitride and Yttrium oxide the worn surface is dominantly a tribolayer severely cracked whereas that ceramics sintered with Yttrium oxide only shows simply the fracture of this grains.

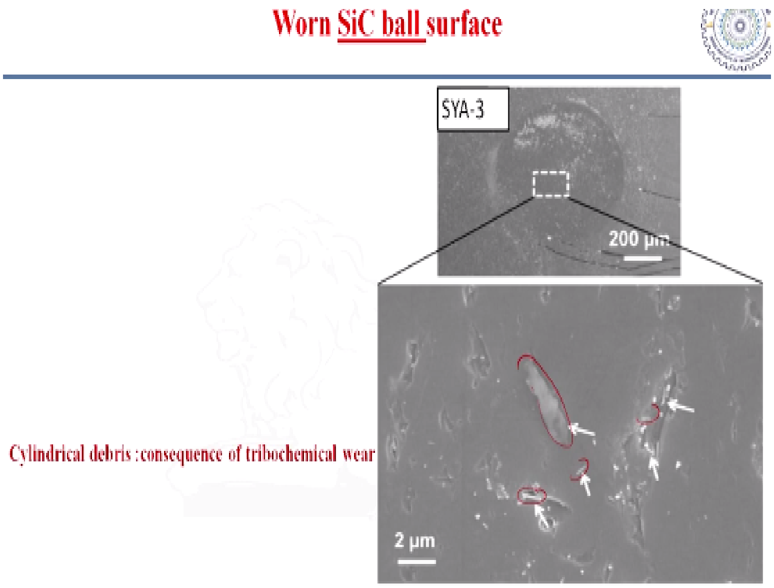
So there is a change from the tribolayer cracking and the removal of material to only the fracture of this material and then removal, but if you look at the silicon carbide ceramics sintered with 3% Yttrium oxide and silicon carbide ceramics sintered with 0.2% Yttrium oxide. The worn surfaces shows a dominantly changed behavior. So the fracture is dominant when it is larger amount of 3% when it is decreased to 0.2%.

The soft surface is strongly tribolayer surface. So it actually indicates there is a tribochemistry playing a role in the wear of ceramics. It is understood widely that silicon carbide when subjected to wear in an ambient conditions reacts with oxygen and then form a silicon oxide and this silicon oxide reacts with moisture in a moderately humid conditions or highly humid conditions then it results Si OH4.

So when you have a smaller amount of additive so you got a more tribolayer dominant whereas a silicon carbide ceramics sintered with aluminum nitride Yttrium oxide content there is a secondary phase which was found in the (()) (21:43) analysis that secondary phase that influences that influences the stress state so it gives a very unstable layer so we have lot of cracks.

Whereas such type of secondary phases are absent when you use this Yttrium oxide particularly with a smaller amount of additive. So these stress states are reduced so you do not find much cracking as you are finding in the; this case. So first of all the secondary phases are absent when there in only Yttrium oxide. The second point is with reduced amount of these additive you got more SiOH4 rich tribolayer which is strongly adhered. So which stops further wear so the wear resistance is increased.

(Refer Slide Time: 22:33)

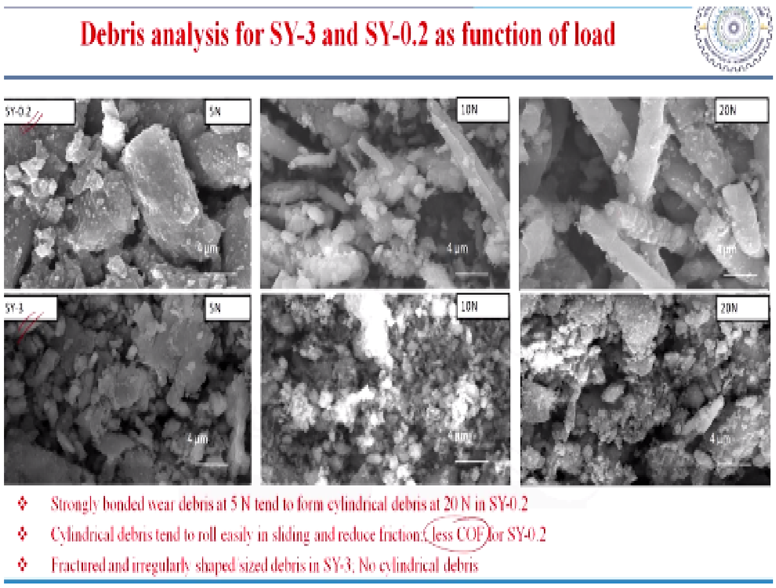


Further investigation on this behavior if you see the silicon carbide ceramics sintered with aluminum nitride and Yttrium oxide the counterbody also shows a signatures of the tribochemistry. So you can see there is a long and thicker cylindrical debris and also thinner cylindrical debris. So these are dispersed on the surface. So it is generally understood as the silicon carbide ceramics were subjected to tribochemical conditions presence.

So this viscous silicon oxyhydride which is removed from the surface this debris connect each other and then form as a cylindrical shape. The cylindrical shaped debris indicates that influence of the tribochemistry here. So there is a fracture of the tribolayer as well, but the fracture is because of the cracking of this tribolayer which is due to the secondary phase influencing the stress state.

But when the secondary phase is not available then you have strongly adherent tribolayers. In both cases you got this tribochemistry influence. The tribochemistry influence can also be supported by the observation of the cylindrical debris.

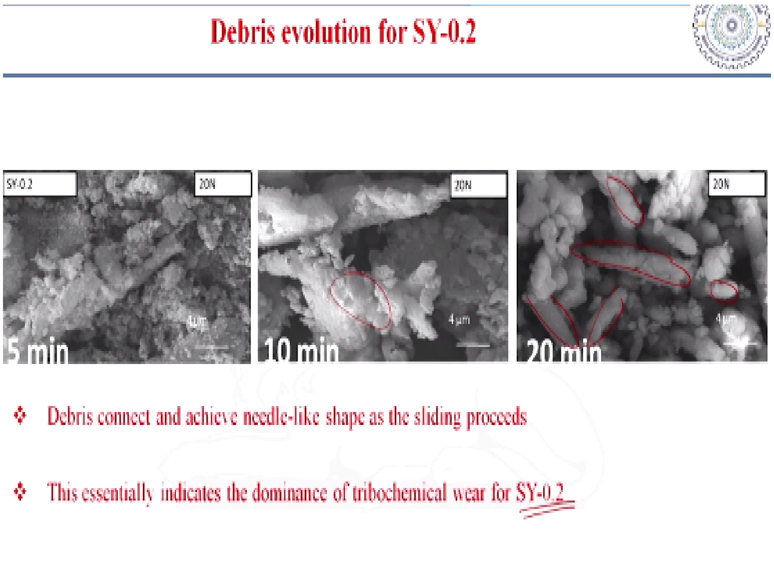
(Refer Slide Time: 24:05)



So the next point is if you see the debris analysis with increase in load from 5 to 10 to 20 Newton. If you see this cylindrical debris tend to roll easily in sliding and then reduce the friction. So if you remember we saw that very less coefficient of friction for this ceramics. So strongly adhered strongly bonded wear debris at 5 Newton tend to form cylindrical debris with increase in load for these silicon carbide ceramics sintered with very small amount of additive.

Whereas the fracture and irregularly shaped or irregularly sized debris are found in the silicon carbon ceramic sintered with 3% of Yttria. There is no presence of the cylindrical debris. This also indicates when you got smaller amount of additive the cylindrical debris is dominant whereas larger amount of additive such as cylindrical debris is less dominant. So when you have cylindrical debris which is a consequence of tribochemical wear so that reduces the friction as well as the wear because it protects from the further wear and also because of this cylindrical debris it is easy to slide so the friction is reduced.

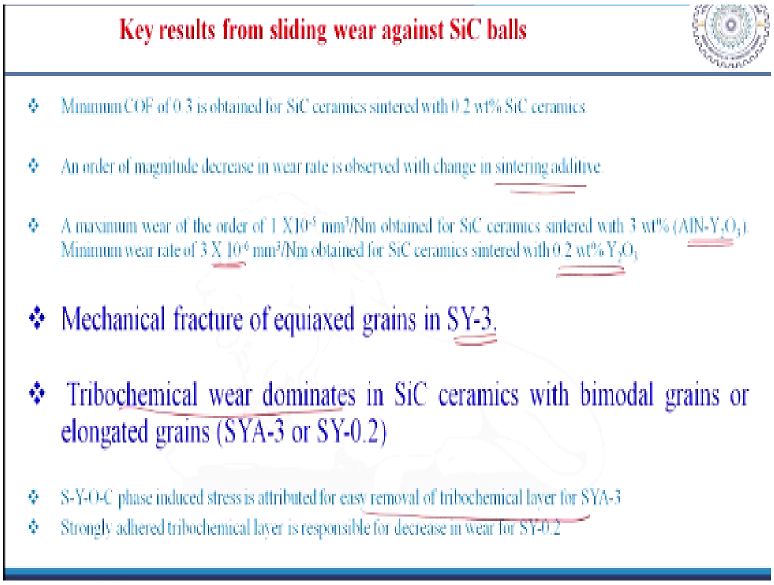
(Refer Slide Time: 25:32)



Now we also investigated the debris formation as a function of time. So initially you can see there is a fracture of the surface and so the debris are very smaller in size and as the time is extended these smaller debris try to connect each other and then form a long cylindrical debris. So debris connect and achieve needle-like shape as the sliding is proceeded and this essentially indicates the dominance of the tribochemical layer observed tribochemical layers.

And its removal observed for the silicon carbide ceramics sintered with very small amount of Yttrium oxide.

(Refer Slide Time: 26:21)



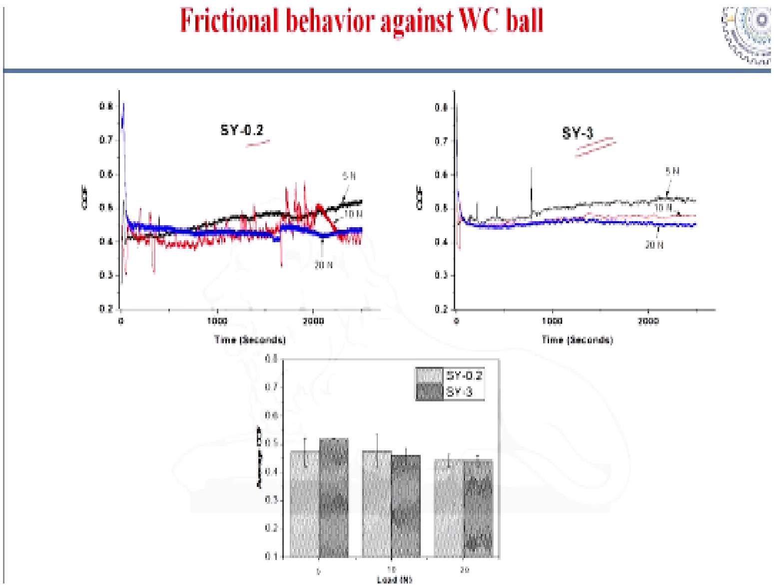
So key results from the sliding wear studies against the silicon carbide balls. Minimum coefficient of friction of 0.3 is obtained for the silicon carbon ceramics sintered with 0.2 weight % of silicon carbide 0.2 weight % of additive and almost an order of magnitude decrease in the wear rate is observed with change in the sintering additive composition.

A maximum wear rate of the order of 1* 10 power -5 mm cube per Newton meter is obtained for the ceramic sintered with 3% aluminum nitride Yttrium oxide sintering additive system whereas very minimum wear of 3*10 power -6 mm cube per Newton meter is obtained for ceramics sintered with very small amount of 0.2% Yttrium oxide. So mechanical fracture of the equiaxed grains is observed for the ceramics sintered with larger amount of Yttrium oxide.

Whereas the tribochemical wear dominates in the ceramics having the bimodal grains or elongated grains. So the secondary phase induced the stress which is attributed for the easy removal of the tribochemical layer. So we got a larger cracking and then removal whereas strongly adhered tribochemical layer is response for the decrease in the wear for the silicon carbide ceramic sintered with 0.25 weight % of Yttrium oxide.

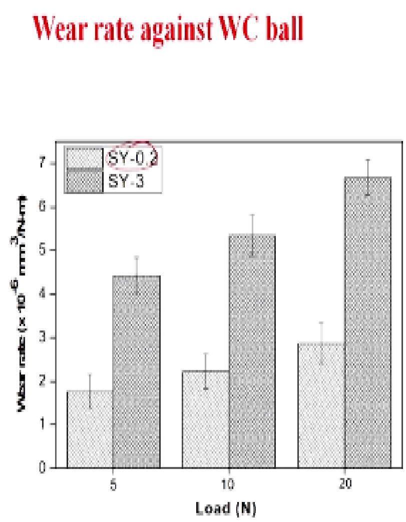
So after this let us understand the behavior of this ceramic wear against Tungsten carbide ball. Tungsten carbide ball is used as a counterbody.

(Refer Slide Time: 28:13)



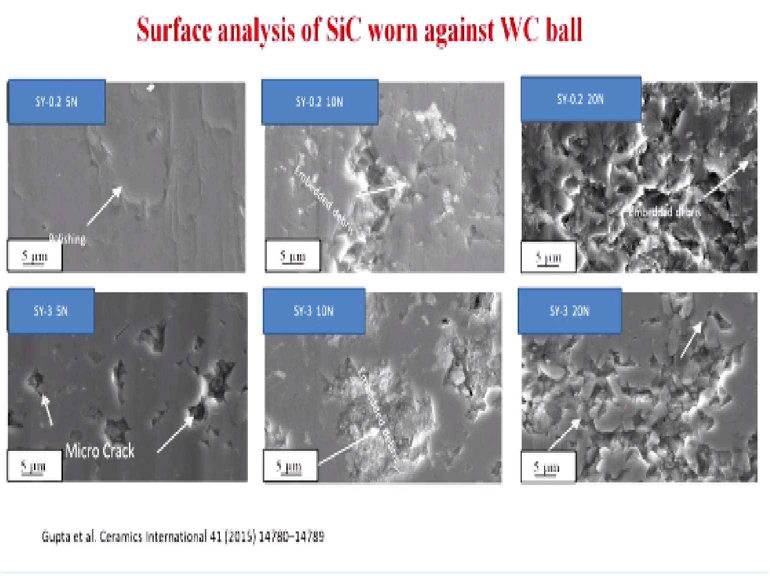
You can see the friction coefficient for these 2 ceramic 0.2% Yttrium oxide containing ceramics and 3% Yttrium oxide containing ceramics. So the friction range is more or less same in the steady state right, but the average friction is found to be almost same for these 2 materials.

(Refer Slide Time: 28:41)



Wear rate shows whenever you have a smaller amount of additive there is a decreased wear.

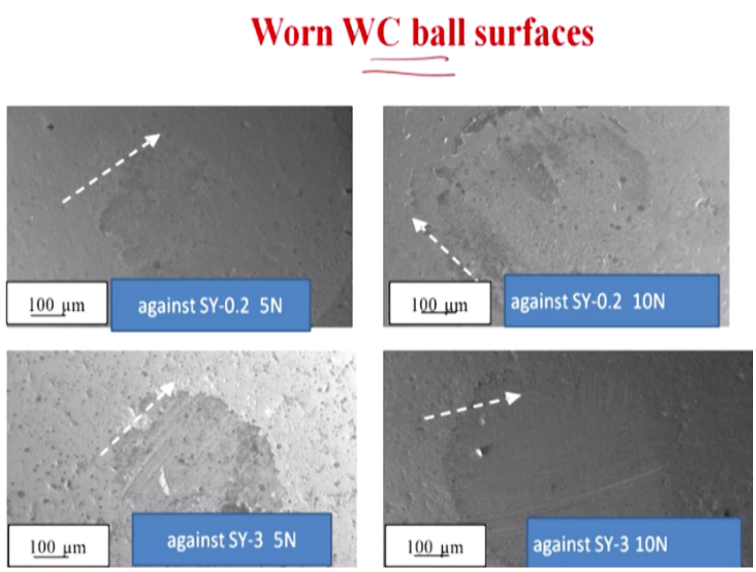
(Refer Slide Time: 28:49)



The surface analysis of the silicon carbide ceramics worn against Tungsten carbide shows only the rough and the abraded surface. This shows there is only the mechanical fracture there is no indication for the tribochemical wear. The silicon carbide ceramics worn against Tungsten carbide ball also shows the polishing and the debris embedding in the fractured surface.

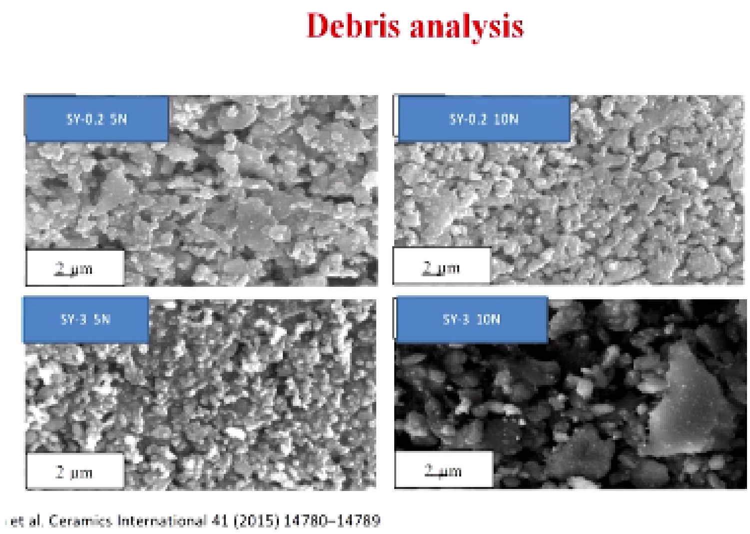
And you can also see a micro cracks and the debris is embedded and this is simply giving the wear by mechanical fracture. There is no tribochemistry involved in this wear of this silicon carbide ceramics against Tungsten carbide ball. So this also shows there is a fracture of this Yttrium oxide. So it is purely a fracture of the silicon carbide grains after the fracture of the second Yttrium oxide.

(Refer Slide Time: 29:49)



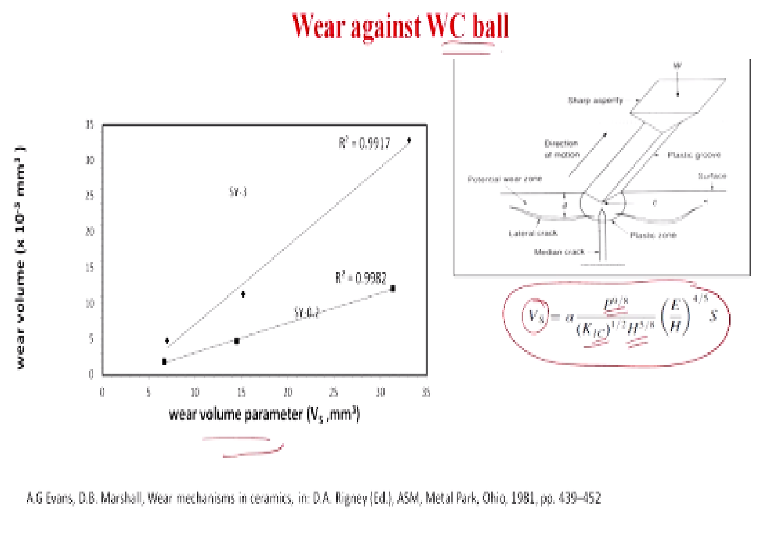
The Tungsten carbide ball also shows it is only the fracture you can see this the abraded surface with all this fracture.

(Refer Slide Time: 30:00)



So the debris analysis further showed again no formation of the cylindrical shape. So all these debris are of irregular shaped and the size there is no cylindrical debris formation.

(Refer Slide Time: 30:18)

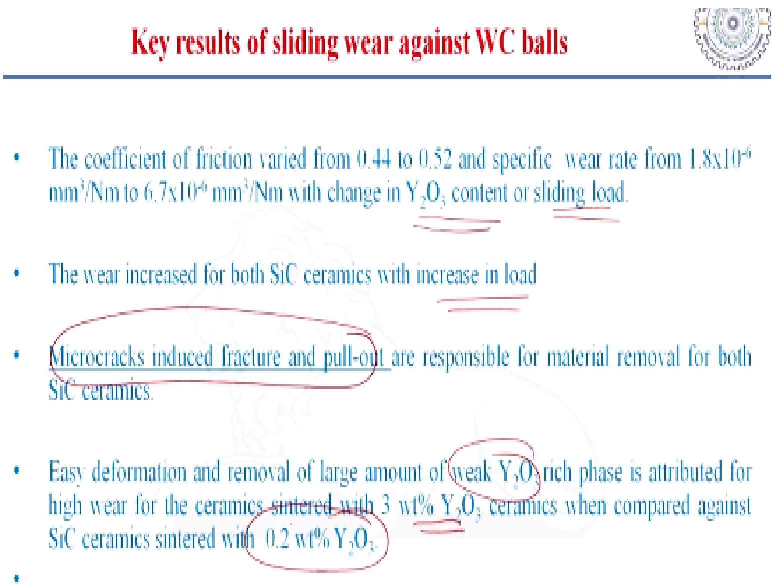


So the information we get from this is when these ceramics were subjected to Tungsten carbide ball they were worn only by the mechanical fracture. So as per the linear fracture mechanics suggested by the Evans and Marshall when a sharp object is slide over the surface of a brittle material. So there forms a plastically deformed region just beneath the contact and because of the continuous sliding.

That means when the load is removed the energy will be dissipated by forming a crack. So you will see a radial median crack as well as the lateral crack. So radial median crack is formed when it is loaded by a sharper object and when the loaded sharper object is moved from the contact then you get a lateral cracks. So the lateral crack model shows the volume of the material removed is proportional to the product of the load applied the fracture toughness and the hardness.

So the wear volume parameter as suggested by this Evans and Marshall was used to studied against the wear volume observed from the present experimental investigation. So this shows a linear dependence. So this particular point indicates the domination of mechanical fracture in the wear of the silicon carbide ceramics when subjected to wear against the Tungsten carbide ball there is no dominance of tribochemistry involved.

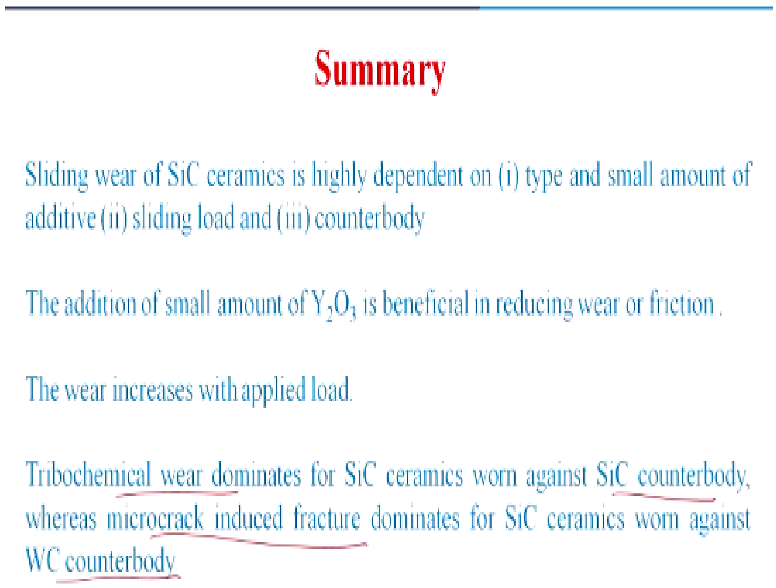
(Refer Slide Time: 32:22)



So the key results from the sliding wear against the Tungsten carbide balls are like this. The coefficient of friction varied from 0.4 to 0.5 and the wear rate from 1.8 to 10 power -6 mm cube per Newton meter to 6.7 10 power -6 mm cube per Newton meter with change in the content of Yttrium oxide or the sliding load. The wear increased for both ceramics with increase in load because of the increase in fracture.

So micro cracks induced fracture and the pull outs of the grains are responsible for the material removal for both silicon carbon ceramics when worn against the Tungsten carbide balls. Easy deformation and removal of large amount of this weaker Yttrium oxide rich phase is attributed for the higher wear for the ceramic sintered with 3% Yttrium oxide seramics when compared against those ceramics sintered with smaller amount of Yttrium oxide additive.

(Refer Slide Time: 33:27)



So let us summarize the results. The sliding wear behavior of silicon carbide is highly depended on the type as well as the small amount of additive and sliding load and counterbody. The addition of small amount of Yttrium oxide is found to be beneficial in reducing the wear or the friction. The wear increases with applied load importantly the tribochemical wear dominates for the silicon carbide ceramics worn against the silicon carbide body counterbody.

Whereas microcrack inducted fracture dominates for the ceramics one against the Tungsten carbide body counterbody. So this particular study is very much useful for understanding the behavior of these liquid phase sintered ceramics sintered with different types of additive systems as well as the content when subjected to wear against different counter bodies and different loading conditions.

So based on the application you can choose the counterbody and the loading conditions for a given additive system. So next lecture we will continue with the silicon carbide, with Tungsten carbide composites wear behavior. Thank you.