Friction and Wear of Materials: Principles and Case Studies
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Lecture - 21
Friction and Wear of HDPE-HA-Al2O3

So welcome back to the NPTEL lectures on friction and wear of materials. So in this particular lecture, I will be discussing one of the case study on high density polyethylene, hydroxyapatite alumina their friction and wear properties. So if you recall in one of the earlier lectures, I have mentioned how to process and how to fabricate this high density polyethylene with ceramic fillers like hydroxyapatite alumina.

And it was emphasized that it was important to develop this composites to mimic the bone properties. So if you remember well that natural bone is a polymer ceramic hybrid composite, so it is a collagen and hydroxyapatite based composites and this collagen and hydroxyapatite source is one is polymer and one is ceramic.

What we have done is that we are trying to see that whether high density polyethylene and ceramic fillers based composites can mimic the natural bone properties in terms of friction and wear different against different matting materials. So other important things that it is important to realize is that ultra high molecular polyethylene is one of the clinically used materials for acetabular socket applications.

And in this ultra high molecular polyethylene, one of the problem is that often against that other matting materials like metals or ceramic this ultra high molecular polyethylene experiences wear and these wear particles often cause inflammatory reactions in vivo. So in order to address the existing clinical problems what we have done, we have developed these new materials using compression molding techniques.

And if you remember well, I have also mentioned that how to optimize the compression molding conditions in terms of the temperature, molding time and so on to develop dense high density polyethylene materials with ceramic fillers. The amount of fillers content is somewhere around 20 to 40% and this loading of these high ceramic fillers has always been a challenge as far as manufacturing of this composites are concerned.

Now we will see in next 25 minutes or so that how these wear properties, friction and wear properties of this HDPE-HA alumina composites when they are fretted against 3 different counter bodies that is alumina, steel as well as zirconia materials. So these are the things I have already discussed at length in one of the earlier lectures.

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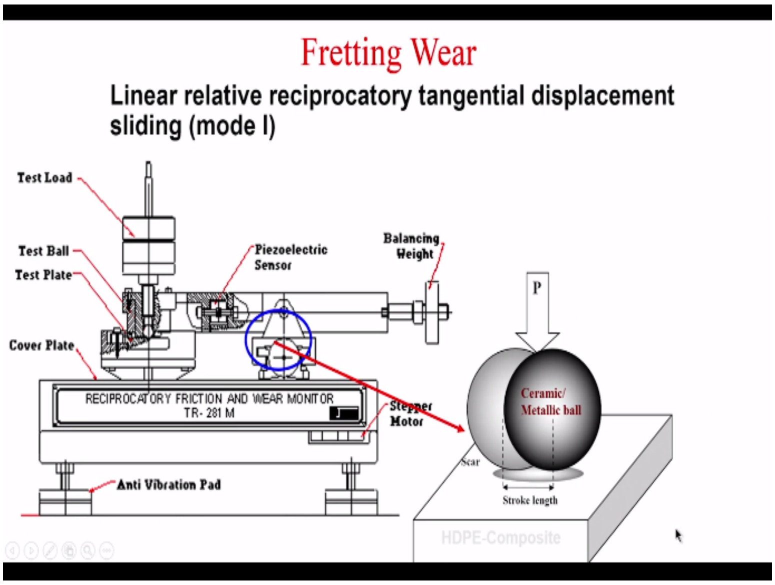

So let us start with the tribological study. These results that I will be showing you in next few slides, these are all published in the open literature and the reader can go through my publications where you can see the more detailed discussion on these particular results. We have used the fretting wear tester and then this functioning of this fretting wear tester. I have also discussed in one of the earlier lectures.

Very quick recap on what I have mentioned earlier, so this is the ball and this is the flat. So this ball on flat that will be there the relative motion at this interface will be actuated by this loading geometry as well as these stepper motor and so on. So as you can see this stepper motor is connected directly to this flat, so essentially cover plate and flat essentially with this stepper motor very small amplitude this relative displacement can be initiated at the ball and flat interface.

And through this piezoelectric sensor you can record the frictional force and which can be recorded online and then frictional force later on can be used to calculate that what is the coefficient of friction. Through this test load this dead weight you can vary the normal load on this ball and flat kind of geometry. So this cartoon is already mentioned, already discussed in earlier lecture.

That you have a ceramic or metallic ball, there is a relative displacement and this is called stroke length. So this stroke length in case of fretting wear varies somewhere between 100 and 200 micron, this is the high density polyethylene hydroxyapatite alumina composites which are used with different compositions as flat material.

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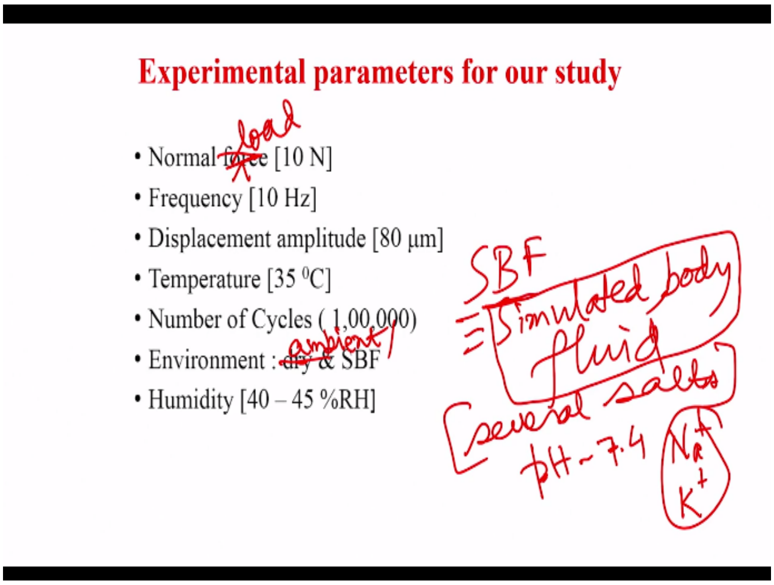

Now while 3 different matting materials are varied in our study. What are the constant operating parameters that we have used in our study? Those are normal force, normal load is like 10 Newton, frequency is 10 hertz, displacement amplitude is 80 micron, temperature is around ambient temperature, number of cycles is 1,00,000 cycles. Now environment the testing environment we have used dry ambient conditions as well as SBF.

That is simulated body fluid, so this SBF essentially stands for simulated body fluid through dry means this is either ambient or SBF and this is your normal load, so normal load is around 10 Newton. Now this simulated body fluid it contains several salt like NaCl and KCl and all this is with the particular ratio.

So that in terms of that pH and pH also it is maintained at around 7.4. in terms of the chloride and concentration in terms of pH in terms of several metallic ions like sodium ions and potassium ions and so on. These will mimic very close to the physiological body environment. So that is the reason that normally in many frictions and wear experiments which involve biomaterials they always use the simulated body fluid okay.

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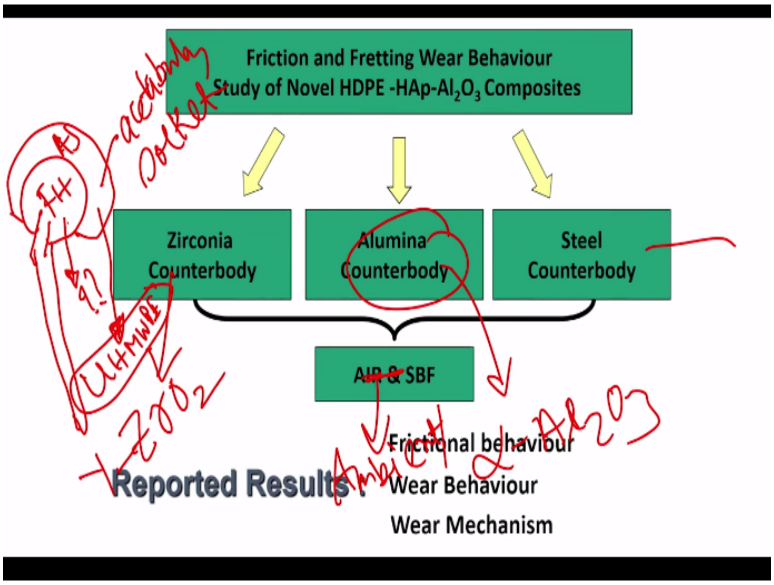

So this is the 3 different counter bodies, this is zirconia, so this is the yttria-stabilized zirconia we have used, this is the alpha alumina we have used and this is the steel bearing steel counter body. Now these different things and then we have used ambient conditions and SBF. So why 3 different solids? Because in real life applications if you recall that you have these femoral stem right.

So you have this femoral stem and on the femoral stem you have this femoral head here and on this femoral head which is contact against this acetabular socket or acetabular liner which is often metal (()) (08:57) that is for non-cemented one and for cemented one if the acetabular liner contains hydroxyapatite and it has good osseointegration and so on. Then, one can use this bone cement.

So this is your femoral head FH and this is your acetabular socket. Now this acetabular socket is typically made up of ultra high molecular weight polyethylene. So in this study we are trying to evaluate that whether ultra high molecular weight polyethylene can be potentially replaced by high density polyethylene HAp alumina and then in order to simulate the clinical scenario lab scale study, it is important to consider what are the femoral head materials.

And these femoral head materials can be either alumina which is used again clinically or zirconia or steel or steel balls. So in order to simulate that kind of environment we have used all the 3 counter bodies in our study.

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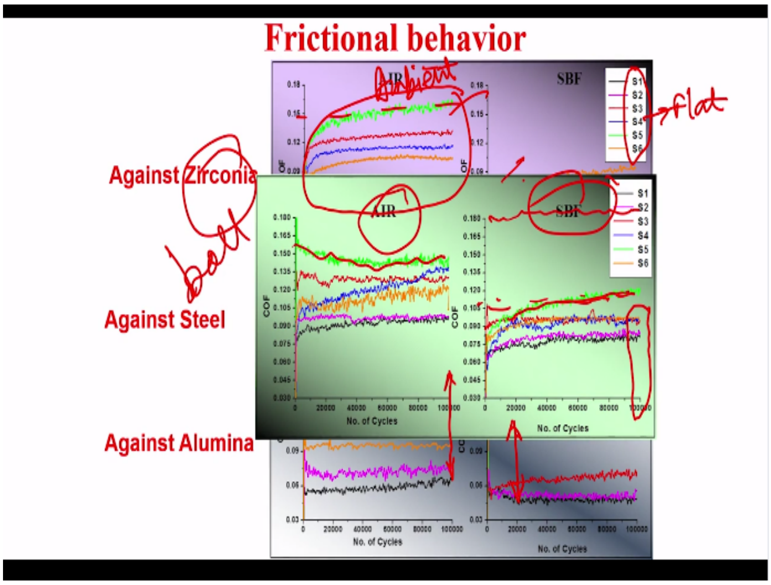

Now in terms of coefficient of friction if you see this is what you see it against zirconia, so one quick observation, this is your ambient results and this is your SBF results. So ambient results you can see that your coefficient of friction can go up to 0.15 and these are the different grades of materials like high density polyethylene if you go back to the slides.

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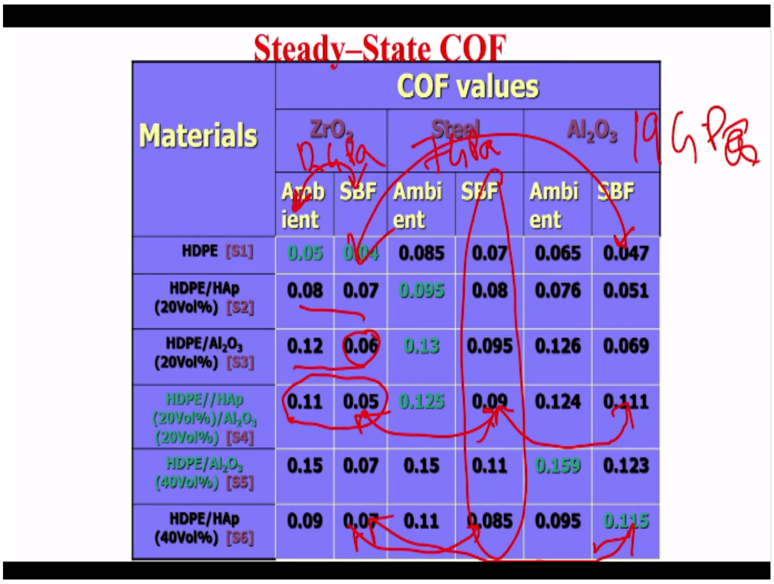
Steady-State COF

Materials	COF values					
	ZrO_2		Steel		Al_2O_3	
	Ambient	SBF	Ambient	SBF	Ambient	SBF
HDPE [S1]	0.05	0.04	0.085	0.07	0.065	0.047
HDPE/HAp (20Vol%) [S2]	0.08	0.07	0.095	0.08	0.076	0.051
HDPE/Al_2O_3 (20Vol%) [S3]	0.12	0.06	0.13	0.095	0.126	0.069
HDPE//HAp (20Vol%)/Al_2O_3 (20Vol%) [S4]	0.11	0.05	0.125	0.09	0.124	0.111
HDPE/Al_2O_3 (40Vol%) [S5]	0.15	0.07	0.15	0.11	0.159	0.123
HDPE/HAp (40Vol%) [S6]	0.09	0.07	0.11	0.085	0.095	0.115

So S1, S2. S1 stands for pure high density polyethylene or (()) (10:34) high density polyethylene, high density polyethylene 20 volume% HAp is your S2, high density polyethylene 20% alumina is your S3, high density polyethylene 20% HAp, 20% alumina is your S4, high density polyethylene 40% alumina is your S5 and high density polyethylene 40% HAp is your S6.

So what you see here that all this S1 to S6 materials these are the flat materials okay and your ball is that alumina or zirconia, this is your ball materials counter body. So all these materials that clearly that from ambient to SBF there is a reduction in coefficient of friction. So systematically for any given material if you take the green one that is S5 it is 0.15 and here it is 0.8 or something.

So even if you can go to this S1 that is or this particular material if you see that is fairly small like 0.03, 0.04 or so on. So against alumina also if you see so after zirconia if you see that what is the situation in case of alumina, in case of alumina also one can make similar observations for example this particular window from 0.15 to 0.6 it is now reduced to 0.9 to 0.5 or something.

So this reduction in this coefficient of friction is certainly quite measurable and quite significant and this is the case for all these different materials okay. So this 0.9 window it has reduced the difference in the coefficient of friction, steady-state coefficient of friction is reduced to 0.04 and if you see in case of steel again, that steel material against the steel counter body so some of the high coefficient of friction is like 0.15 but whereas in case of steel even the green one that is S5 that also goes to 0.11.

So this reduction maybe is little lower in case of the steel counter body but certainly if you compare with respect to ambient versus simulated body fluid, certainly there is a push towards the lower coefficient of friction in case of simulated body fluid, so this is what is the summary. If you see this is your zirconia steel counter body, this is alumina and this is sorry this is steel and this is alumina.

And if you now compare with respect to ambient versus SBF against each of the counter body you will see there is a reduction for example alumina it goes from 0.1 to 2.06. If it goes to high density polyethylene HAp and alumina composites, then it goes from 0.11 to 0.05. So it is almost like 50% or almost like half of that of that what you measure in the ambient conditions.

But if you compare the frictional coefficient measured in the SBF so what you notice that there is a tendency in case of the steel coefficient of friction is relatively higher. For any materials if you compare 0.07 to 0.09 or 0.05 to 0.09 so any material if you see that SBF results when all the fretting parameters remain constant so we see that when we use the steel as a counter body, there is an increase in the coefficient of friction.

Now in case of alumina again this frictional coefficient is relatively higher compared to steel but if you see frictional coefficient between zirconia and alumina it is many times either comparable or in case of alumina little bit higher. Remember the hardness of alumina is around 19 gigapascal, hardness of zirconia is around 12 gigapascal, hardness of steel it is 7 gigapascal, so if you look at the differences in the hardness.

So alumina is for the hardness of all these materials so but then I will come back to that what is the influence of hardness and so on on the wear mechanisms later on but at this point we can see that there is a difference in the physical properties of the matting materials that is the balls and we do see there is a difference in the coefficient of friction when we compare only the simulated body fluid results okay.

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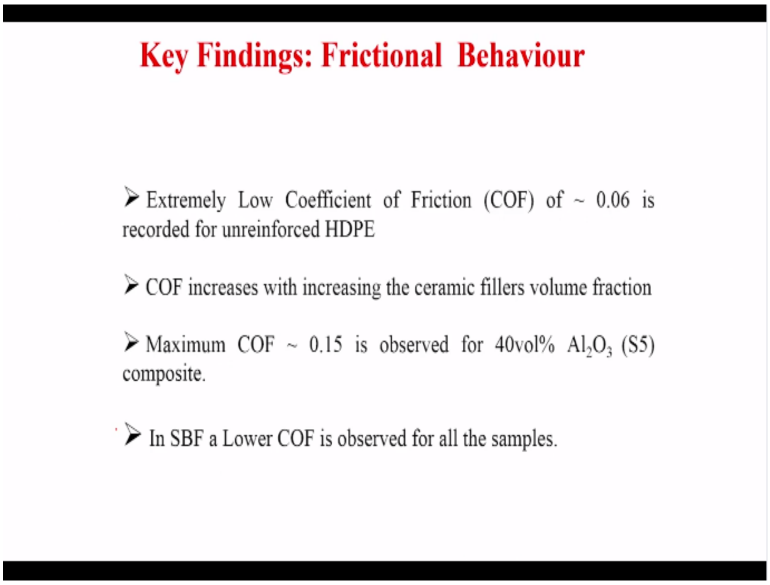

So now these are the key findings, so certainly that coefficient of friction increases with the ceramic fillers and maximum coefficient of friction is 0.15, in SBF lower COF is observed for all the samples.

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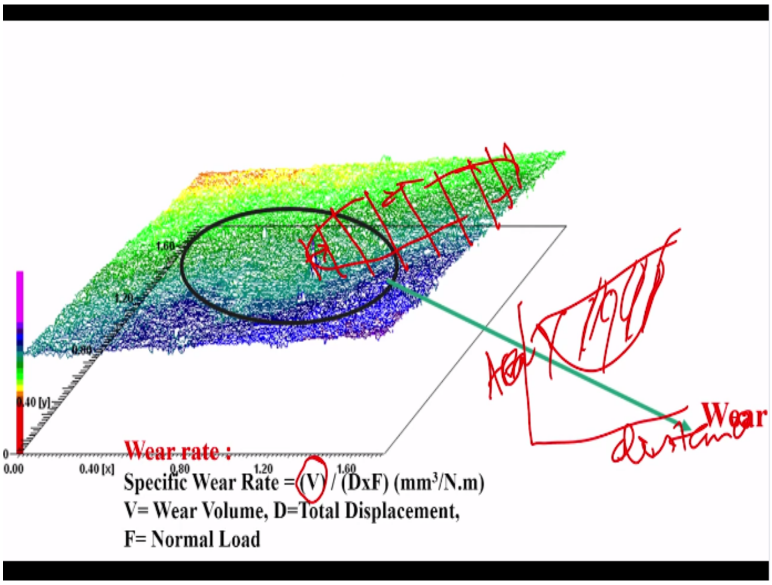

Next, is the wear rate measurements, now this is the typical the wear rates, you know wear scar that is formed on the material surfaces. I have mentioned in one of the earlier lectures that what you do, you take the various 2-D profiles at various positions spatial locations right on the wear and then you plot area of each profile as a function of distance and then you get this kind of a curve and then you take area under the curve then you get the volume.

And this volume is this wear volume okay, so this volume is the wear volume and then this wear volume you can see that so this wear volume you can use in calculating the specific wear rate, so specific wear rate is nothing but V/D times F and V is the wear volume, D is the total displacement like total fretted displacement and F is a normal load. So then you can get millimeter cube and newton meter.

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Wear Rate Against Different Counterbody

Materials	WEAR RATE ($mm^3/N.m$)					
	ZrO_2 ($\sim x\ 10^{-6}$ $mm^3/N.m$)		Steel ($\sim x\ 10^{-6}$ $mm^3/N.m$)		Al_2O_3 ($\sim x\ 10^{-7}$ $mm^3/N.m$)	
	Ambient	SBF	Ambient	SBF	Ambient	SBF
HDPE [S1]	13.75	8.1	25.2	11.5	89.15	83.18
HDPE/HAp (20Vol%) [S2]	7.1	4.9	9.5	7.8	48.75	46.11
HDPE/Al_2O_3 (20Vol%) [S3]	4.3	2.28	8.7	4.6	41.62	33.25
HDPE//HAp (20Vol%)/Al_2O_3 (20Vol%) [S4]	1.78	1.08	3.87	2.3	7.19	5.92
HDPE/Al_2O_3 (40Vol%) [S5]	0.9	0.2	2.75	1.83	3.13	1.28
HDPE/HAp (40Vol%) [S6]	3.9	3.4	6.6	4.9	24.53	29.61

Now wear rate against different counter body, now if you see that this particular case you can see that what is this is the 10 to the power -6 so this is the wear rate order of magnitude, this is 10 to the power -6 and this is 10 to the power -7. So in case of alumina generally there is a one order of magnitude difference but if you look at this 10 to the power -7 here this is now 83*10 to the power -7 is nothing but 8*8.3*10 to the power -6 right 83*10 to the power -7 is nothing but 8.3*10 to the power -6.

So that way this value and this value is comparable. Now let us look at this table little closely and if you look at little closely you will see that if you compare between ambient and SBF, there is a reduction in the wear volume like 7.1 goes to 4.5, 4.3 goes to 2.28 and so on. Similar observations you can make in case of the steel counter body also, 25.2 goes to 11.5, 3.9 goes to 2.3.

In case of alumina, 89 goes to 83, 41 goes to 33 so like friction coefficient there is also a systematic reduction in the wear rate against each of the counter body when in simulated body fluid environment compared to the test carried out in the ambient conditions. Now if you look at the SBF results alone, so if you look at SBF results alone what you notice here so in this SBF results that in case of HDPE it is 8.1*10 to the power -6, it is 83*10 to the power -7, it is almost comparable.

And however if you look at that HDPE HAp alumina it is 1.1*10 to the power -6 and here it is 5.9 to 10 to the -7, 5.9 to 10 to the -7 means it is 0.5*10 to the power -6, what it means that in case of the high density polyethylene HAp alumina S4 composites so wear rate is kind of reduced, it is the alumina compared to that of the zirconia whereas in case of steel typically the wear rate is much higher.

So if you look at in case of the steel, the wear rate in case of steel if you see that 1.08 goes to 2.3 almost like double because 10 to the power -6 and 10 to the power -6 that means magnitude of the wear is similar. Now when you go to 2 to 1.83 again 9 times higher and if you go to HDPE 20% alumina so it again go from 2.28 to 4.6 so again it is like two times higher.

So typically our observation is that while in case of alumina the wear rate in simulated body fluid is either comparable or reduced for a given polymeric composition, for a given polymer ceramic composition but in case of steel typically the wear rate even in the simulated body fluid is higher compared to that measured with zirconia or alumina matting materials.

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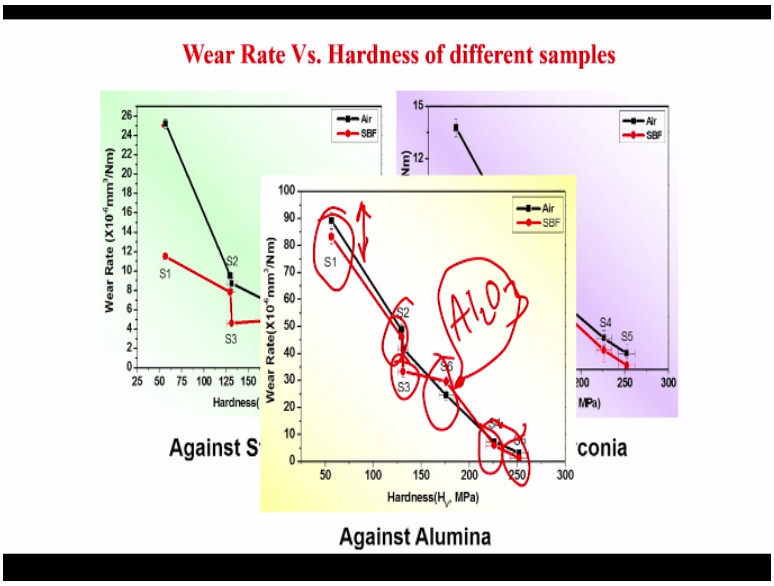

Now in one of the earlier slide, I have mentioned that hardness can be hardness differences should be considered while considering the differences in the wear for example wear rate. Now in this slide what you see that that wear rate is plotted against hardness of the flat materials. Now we are not considering here the hardness of matting materials but this is against steel.

So when steel is used as a counter body when it goes from S1 to S5 you see there is a reduction in the ambient conditions okay but there is also a reduction in the simulated body fluid but by far that reduction in ambient is much more significant compared to reduction in simulated body fluid. What it means that since simulated body fluid any wear rate is lower, but still we have observed particularly in case of S5 the much lower wear rate can be measured against steel.

In case of zirconia, what you observe that when you go from ambient conditions here to that of the SBF, again a similar qualitative trend has been observed and this is the scenario for alumina and in case of alumina as a counter body what you have observed although for S1 this wear rate is comparable both in alumina and SBF but what is interesting is that that is for the pure HDPE or unreinforced HDPE in case of steel and zirconia there is a difference for S1 composite to S1 wear.

But here this difference is negligible or absolutely there is not much difference because (()) (22:51) the same is true for S2 and same is true for S3, S6, S4 and S5. So against that alumina counter body this is a very interesting observation or intriguing observations what we have noticed that all the materials they experience similar wear irrespective of ambient or simulated body fluid environment.

However, there is a difference among the flat materials itself and then similar qualitative trend was also observed like in case of steel or zirconia counter body.

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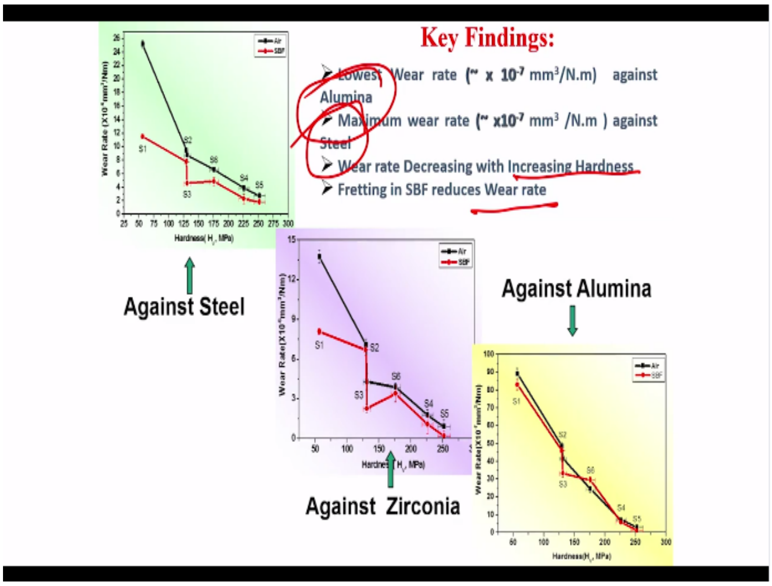

So this is the key findings that lowest wear rate is moreover observed in case of alumina maximum wear rate in case of steel and then wear rate decreases with increasing hardness. What it points out to us that if one remembers the Archard law for the abrasive wear so in case of abrasive wear dominated situation that typically the wear rate decreases with the hardness of the material.

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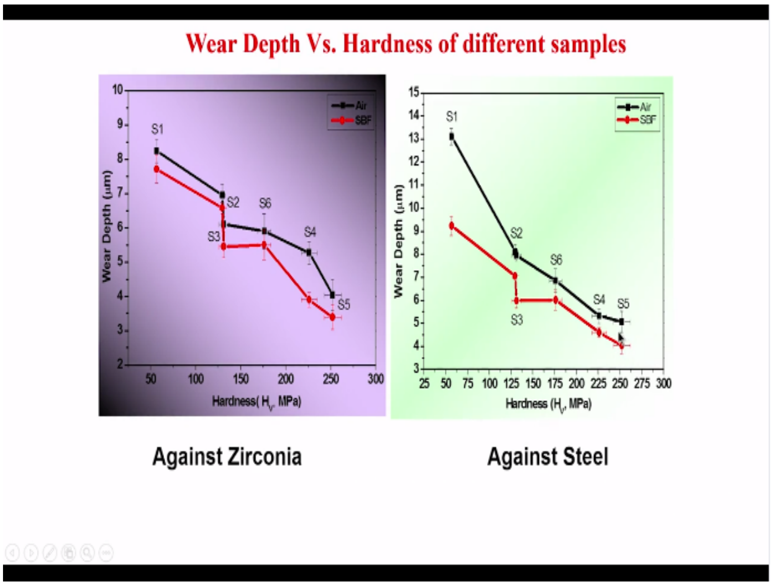

Now the severity of wear is not only measured by the wear rate but also measured by the wear depth. Now here you see that how this wear depth decreases with hardness of the materials. So wear depth here means that is the maximum wear depth so if you take the several profiles and if you lined up and if you see this is the maximum I am talking about this maximum which is reported along y-axis here.

So essentially what you see that wear depth is <10 micron that is the first observation, second observation is that although there is an apparent decrease in the wear depth not apparent there is a clear decrease in the wear depth with that of the flat hardness of this material or hardness of the flat material but the qualitative trend is almost similar to that of the variation of the wear rate against hardness.

In case of steel again what we have noticed is that that if you increase the hardness of the material typically wear depth decreases but what is interesting here that steel typically whereas mode in case of the pure HDPE but when it goes to S2 to S5, the wear rate is 5 micron or below that.

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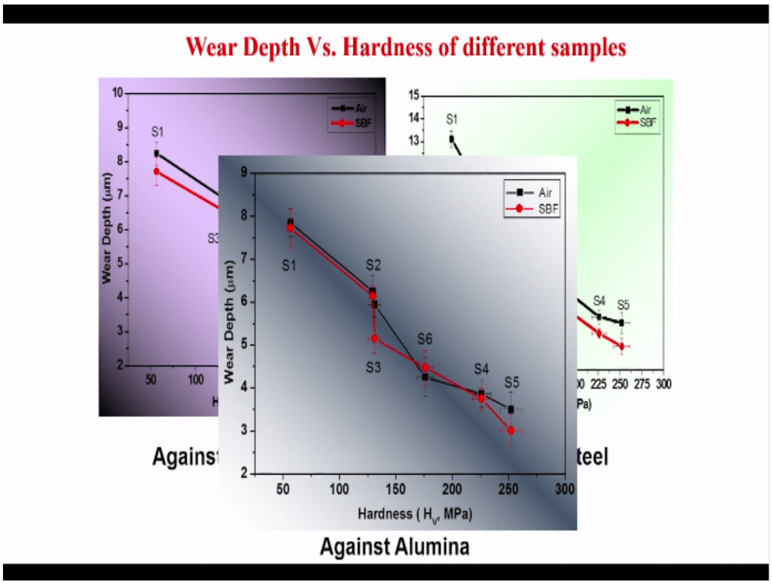

And in case of alumina as you have seen in case of the wear rate also that is absolutely no difference, no statistically significant difference between the wear depth what you measured in the ambient environment and wear depth what you measured in simulated body fluid after fretting testing.

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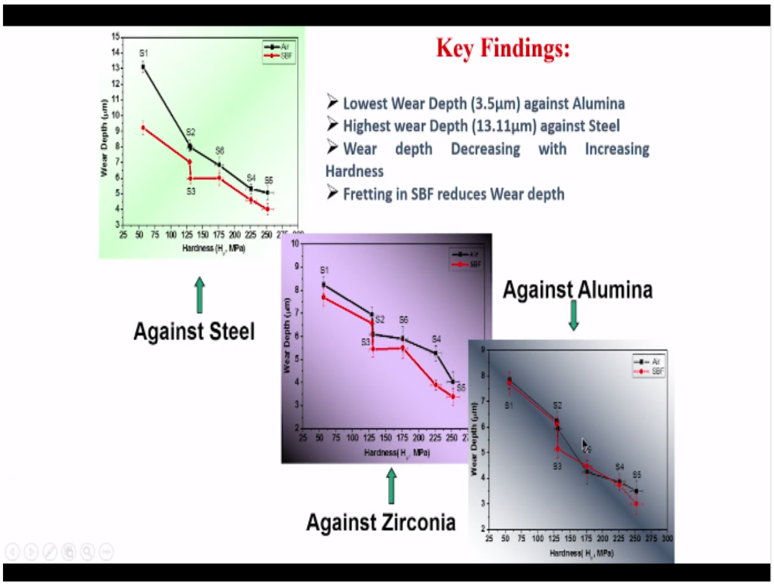

And this is the 3 comparison against steel, zirconia and alumina, what are the findings in terms of the wear rate variation, wear depth variation in terms of hardness.

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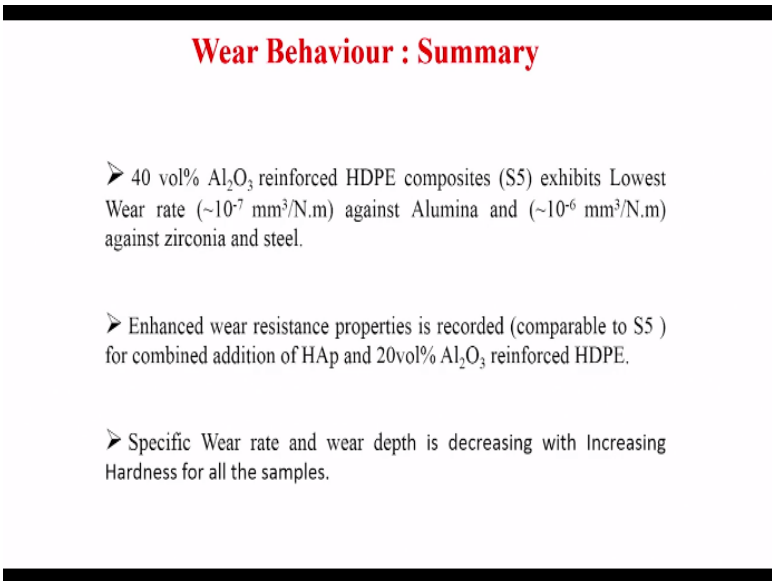

Now this is the typical summary of the wear in terms of quantitative analysis of the wear rate and wear depth.

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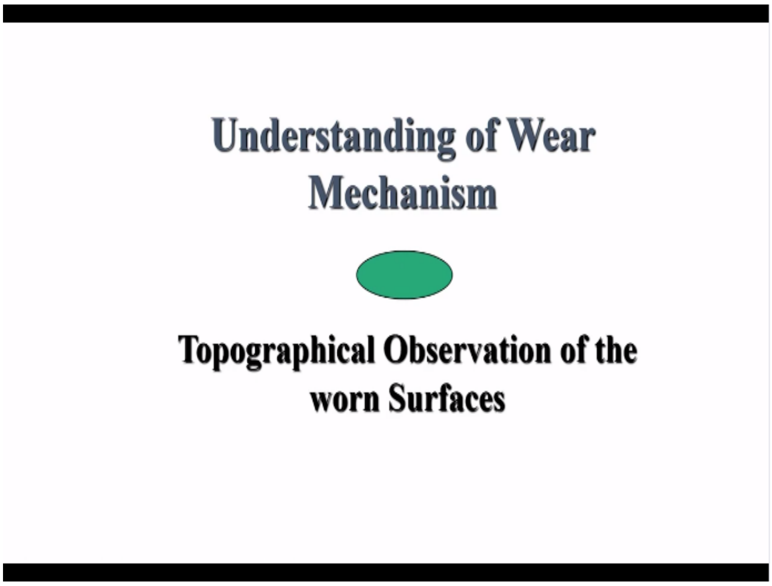

But more interestingly as I said before that wear mechanism is what we normally investigate or what we normally very excited about when it comes to the domain of the material science.

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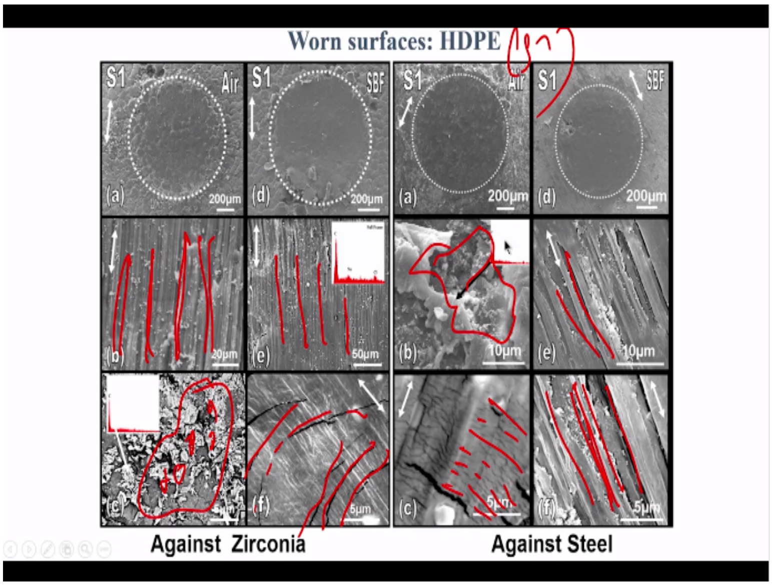

And so therefore we have invested lot of efforts to understand that how these wear mechanism they are different. So let us look at first that HDPE that is the S1 sample and HDPE what you see that there is a very clear signature of the very deep abrasive groups and scratches which we have observed in ambient conditions. In the SBF that scratches the severity of the abrasion is reduced.

But what is more interesting is that there is some concentric cracking what we have observed on the fretted surface and this is the chunk of the wear debris particles and if you see these are mostly that polymeric wear debris particles what we have observed against when the materials are tested against zirconia. Now what happens in case of steel, steel since the wear rate is higher you can see much more deeper abrasive scratches.

And if you look at some of these deeper abrasive groups you can see there are signs of abrasions and also cracking there observed. Like in the previous case, we have also seen there are microcracks coalesces together to form a concentric cracking in case of the ambient conditions.

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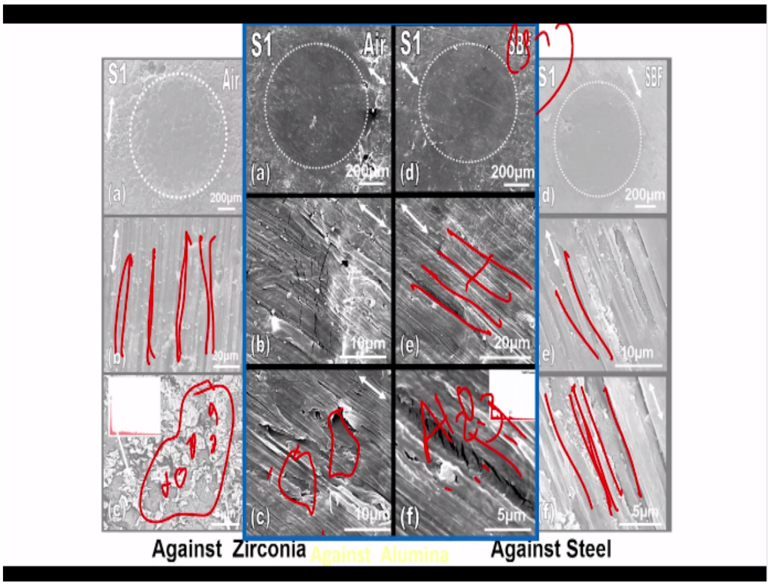

And this is what happens when you do the test against alumina as a counter body, so this is the case for alumina as the counter body and what you see in case of alumina again there is signs of abrasive wear but certainly some of the signatures of the very severe wear as in case of steel were not found after the test with alumina.

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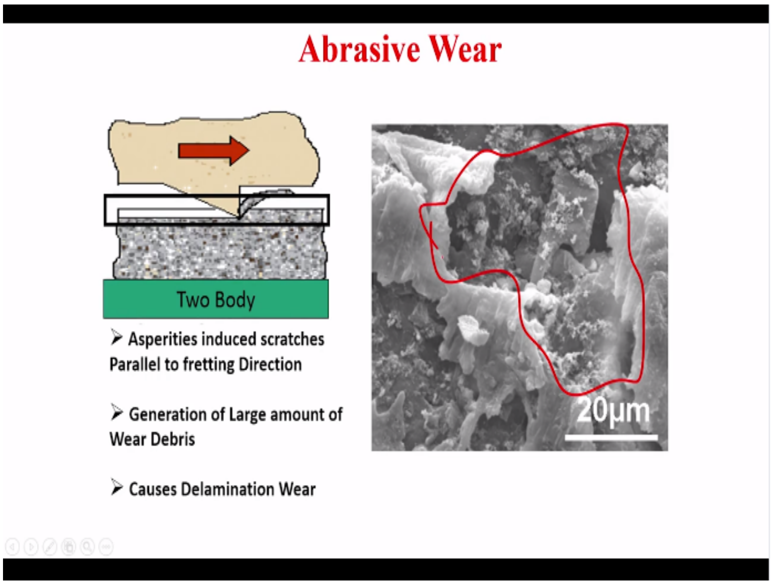

Now just a brief background to the abrasive wear. Abrasive wear is that the harder asperities they always scratch away the material from the softer materials and that leads to large amount of wear debris and ultimately when it continues it also causes delamination wear. These are some of the observations what we have found and these are like signature of the delamination wear also.

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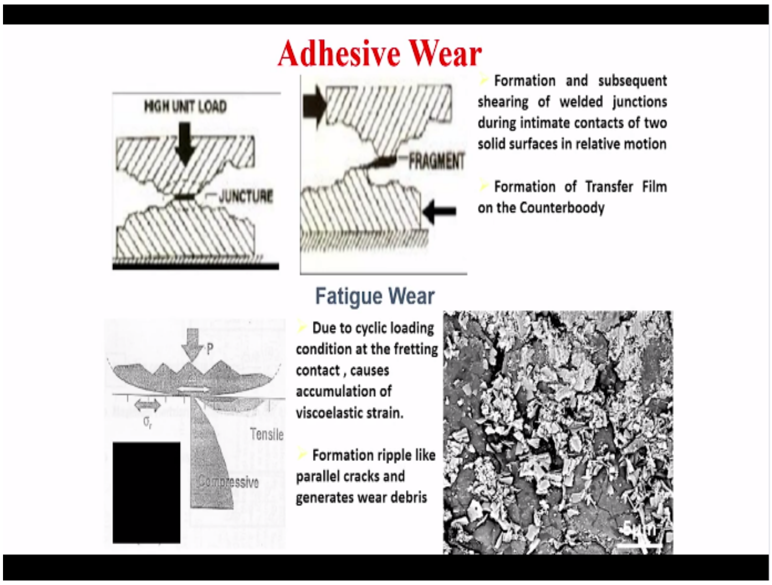

And this is the case of adhesive wear, adhesive wear is mostly taken place in case of the two matting materials of similar compositions and there is also transfer film on the counter body and there is a fatigue wear. Fatigue wear essentially, fatigue wear is experienced when there is a cyclic loading conditions of the fretting contact.

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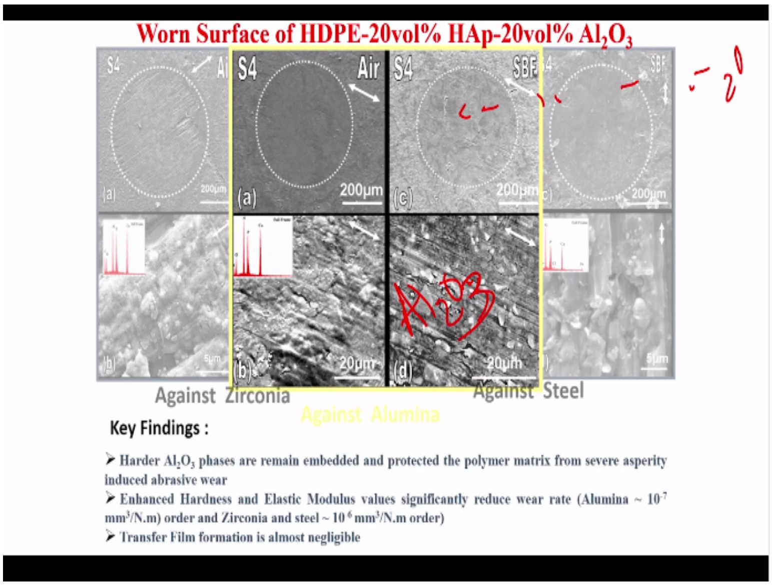

Now what happens, we have done very systematic analysis for all the materials but what is more important for you to see what is the fundamental differences in the worn surface morphology in case of that HDPE 20% HAp and 20% alumina when compared to that of the pure HDPE. Now what you notice here in case of the ambient conditions and SBF simulated body fluid and when you do zirconia as a counter body, severity of abrasive wear is certainly reduced and in zirconia you will also see there are hydroxyapatite particles here you can see.

And then you can see that some of the EDS compositional analysis spectra you can see that peaks of calcium and phosphorus because of the hydroxyapatite pattern which is present and the similar things we have seen in case of the steel and more importantly when it goes to alumina as a counter body so these are the peaks that you can see against the alumina as a counter body and in case of alumina again if you see that there is a severity of the abrasion is far more reduced.

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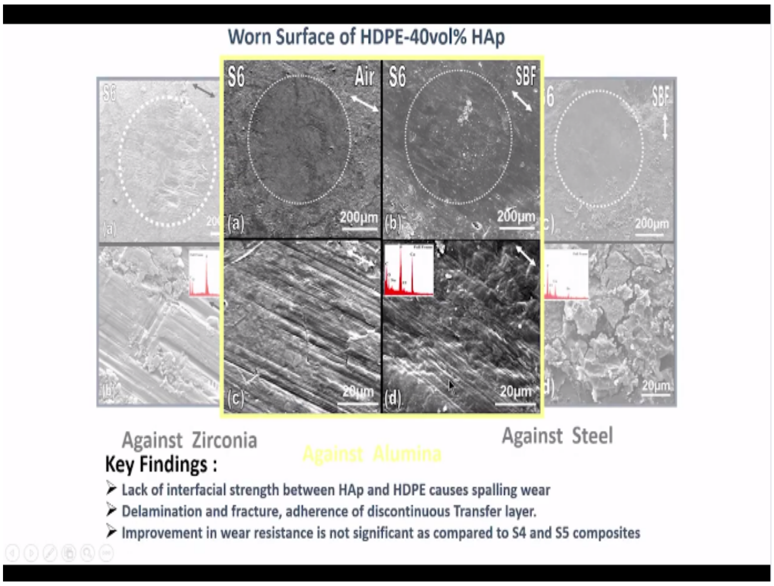

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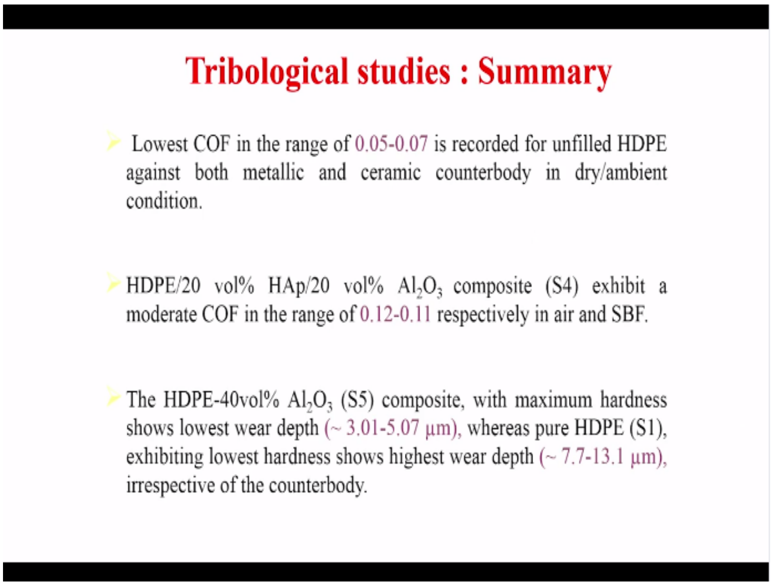

So these are the other materials that we also have investigated and this is the summary that HDPE 20% HAp 20% alumina exhibit a moderate COF and also their wear depth is fairly small <10 micron in this one.

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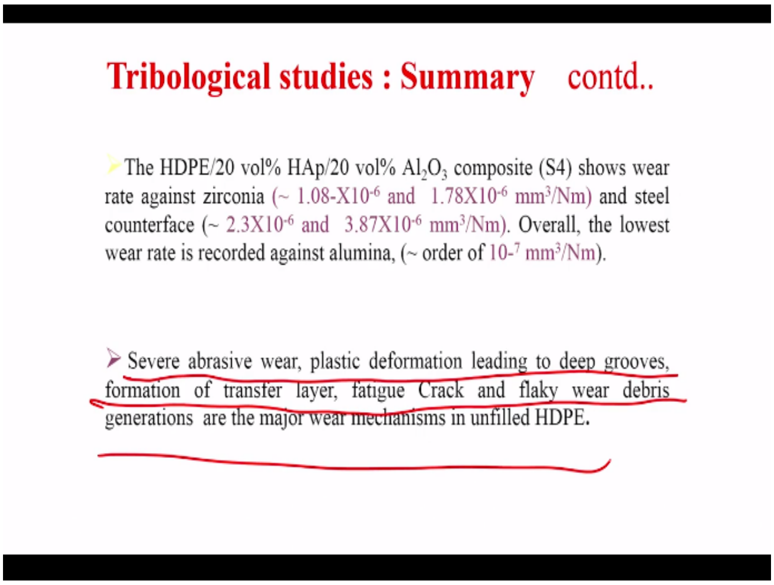

And then they have mostly experienced abrasive and plastic deformation leading to the groove, fatigue crack and flaky wear debris at this case of unfilled HDPE. Thank you.