Friction and Wear of Materials: Principles and Case Studies

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Lecture - 11
Overview of Tribological Materials

So in this lecture, I will discuss some of the major materials which are used for tribological applications.

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So this will essentially as in next this will be an extension of one of my earlier lectures where I have mentioned some of the generic material classes like ceramics, metals and polymers. So we will see that what are the different application areas that where these materials are used to provide desired wear resistance or to reduce the friction and wear resistance.

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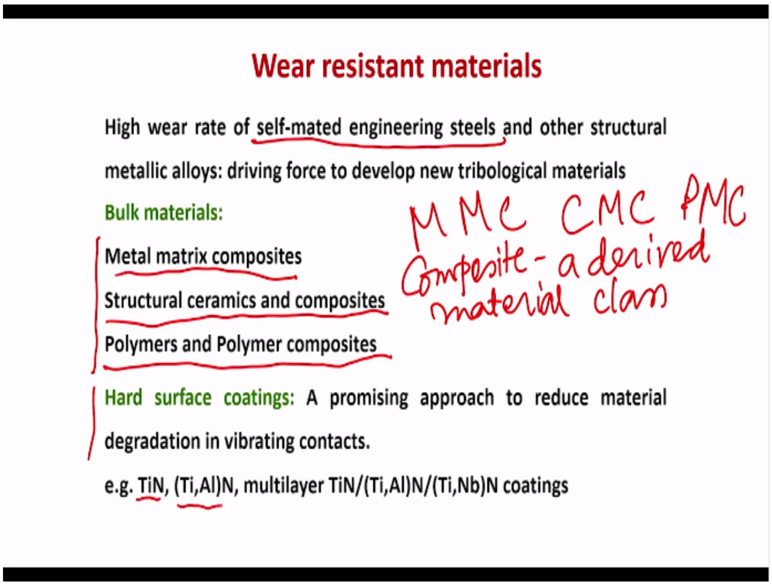

So the major motivation to develop new materials for wear resistance applications comes from the fact that most of the steels, engineering steels they experience extremely high wear and this actually drives the development of all these new materials. So one of the bulk material is metal matrix composites, second one is the ceramics and composites, third one polymers and polymer composites okay.

So this MMC, CMC and PMC so first thing one should know what is composite. So composite essentially derived material class okay, a derived material class which can constitute metal, ceramics and polymers but one of the metals or ceramics or polymers will act as a matrix and another phase like it can be either metal, ceramics and polymer can be called as a reinforcement in the matrix.

So idea of developing composite is to improve the certain properties like mechanical properties of the composite and that is important so what you can see if I extend our discussion for that that essentially this one particular material as I said metal, ceramics and polymers in the composite.

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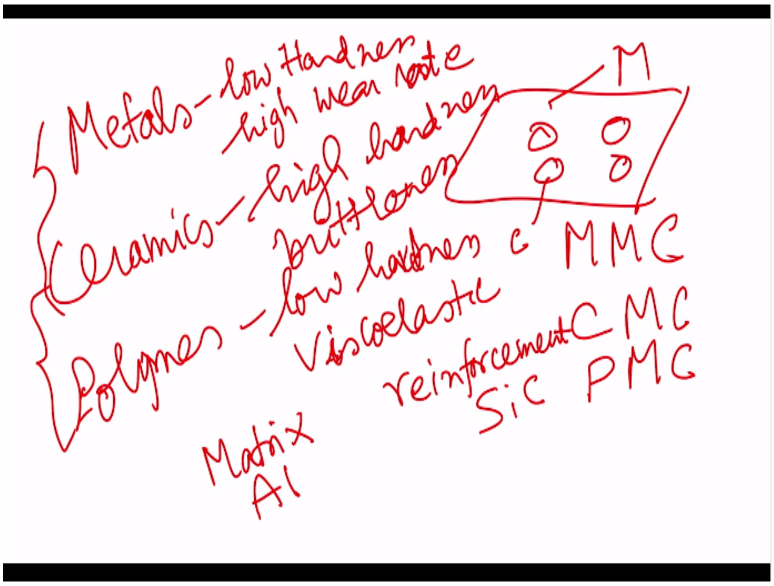

So if you see as a block so if you have some dispersed second phase so it can be metals and this dispersed second phase can be ceramic. Now from this simple sketch you can see that ceramics the phase fraction of the ceramic is fairly low and metal fraction is much larger. So we will call it as a MMC, so metal matrix composite. So whichever will form the matrix we name designate that composite by that.

So if it is ceramic matrix composite you know that ceramic is a main constituent phase of the matrix. If it is a polymer matrix composite, you know polymer is the major phase or major constituent phase that is why it is called polymer matrix composite. Now what is need for development of the composite? The need for development of the composite is the fact that metals for example.

Metals are very good because it is weldable, it has very good ductility but it has a low hardness so let us say low hardness and also metals has high wear rate, high wear rate means it has a low wear resistance, high wear rate but in ceramics if you see ceramics has a very high hardness but it is extremely brittle right. So brittleness is the major bottleneck of the ceramic whereas polymer so polymer what happen polymer has very low hardness or strength properties.

But it has some viscoelastic properties which sometimes is very advantageous, so idea of composite is that you combine the advantageous properties so that idea of composite is essentially you have both the phases in the composite material and you aim to attain higher properties or larger properties of some specific properties. So that is very important in case of the composite.

So this is very important so metal ceramics and polymers and then I mentioned that one of the phases can constitute matrix and another phase will constitute the reinforcement. For aluminum silicon carbide composite, aluminium is a matrix, silicon carbide is a reinforcement right just for to give an example. Now these are the 3 primary material classes sorry these are the 3 derived material classes and primary classes is metal, ceramics and polymers.

What is the coatings? Coatings is another approach because bulk of the engineering applications for bulk of the engineering applications you need structural materials like steel and on the steel you give some coatings like you know you give some very hard coatings and as I mentioned in the earlier lecture these coatings can be either titanium nitrate coating or titanium aluminum nitrate coating or multilayer coatings.

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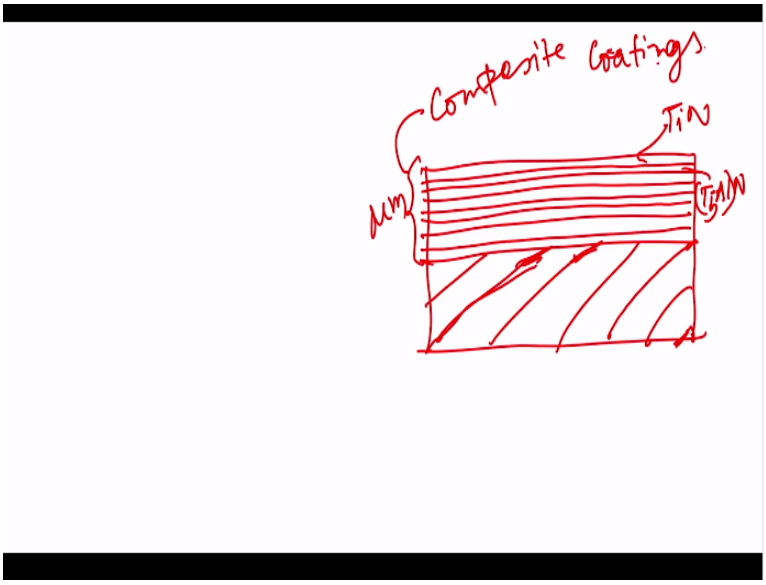

So if you look at the structure for example if you have this is your bulk material and then coatings can be very thin coatings where thickness can be <100 nanometer but you can deposit multiple coatings and these coatings can be either titanium nitrate or titanium aluminium nitride and so on. So essentially this different coatings, different layers are deposited on the top of each other.

And this will constitute as a few micrometer coatings okay. This will constitute few micrometer so as a result what you can do, what you can realize that essentially bulk material can be used, you do not need to replace a bulk material but since friction and wear is a surface dominated properties so you get a coating which is essentially made of the hard material like ceramics and then your bulk material remained underlying bulk material is there.

But the question is that can you call these kind of situations as a composite material? No. what we can at best mention? You can mention is at a composite coatings, why composite coatings? Because it is not a single layer coatings but it is a multilayer coatings and in this multilayer coatings each layer has a different ceramic composition. That is why you can call this as composite coatings okay.

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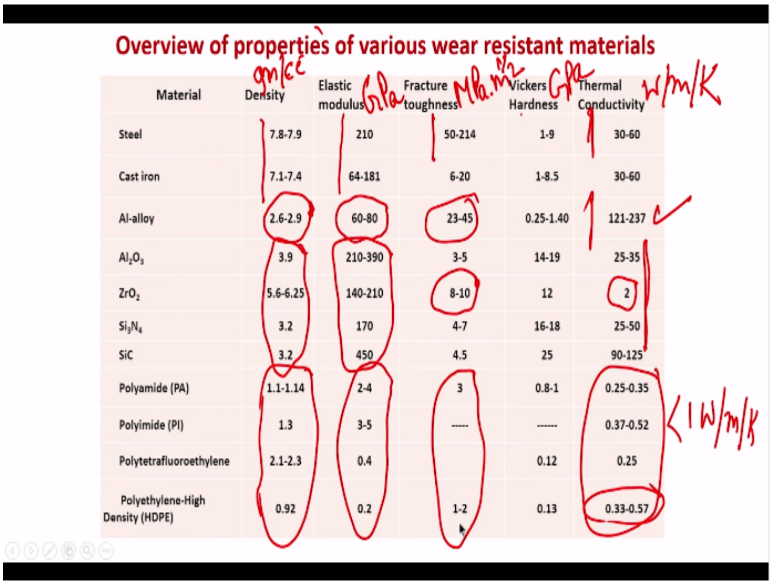

Overview of properties of various wear resistant materials

Material	Density gm/cc	Elastic modulus GPa	Fracture toughness MPa.m^1/2	Vickers Hardness GPa	Thermal Conductivity W/m/K
Steel	7.8-7.9	210	50-214	1-9	30-60
Cast iron	7.1-7.4	64-181	6-20	1-8.5	30-60
Al-alloy	2.6-2.9	60-80	23-45	0.25-1.40	121-237
Al_2O_3	3.9	210-390	3-5	14-19	25-35
ZrO_2	5.6-6.25	140-210	8-10	12	2
Si_3N_4	3.2	170	4-7	16-18	25-50
SiC	3.2	450	4.5	25	90-125
Polyamide (PA)	1.1-1.14	2-4	3	0.8-1	0.25-0.35
Polyimide (PI)	1.3	3-5	-----	------	0.37-0.52
Polytetrafluoroethylene	2.1-2.3	0.4		0.12	0.25
Polyethylene-High Density (HDPE)	0.92	0.2	1-2	0.13	0.33-0.57

<1 W/m/K

Now this table essentially shows you that what are the different metal, ceramics and polymers which are widely used for different tribological applications. Now if you look at the steel, now steel has a this kind of physical properties, it has a density around 7.8, cast iron is close to 7, elastic modulus is fairly high 210, fractured toughness is also can be high, thermal conductivity is kind of moderate 30 to 60.

Now if you go to aluminum alloys thermal conductivity is very high, density is almost like one-third of that of the steel 2.6. So for the low density materials aluminium alloy is preferred. Elastic modulus also can be very low here 60 to 80, fractured toughness is lower than the steel and thermal conductivity is very high. Now if you go to ceramics there the thermal conductivity is lower.

What it means that ceramics if you use ceramics or two materials of ceramics then the heat generation will be very high simply because of thermal conductivity is fairly low okay but at the same time you must recognize that many of the ceramics has low density like alumina is 3.9 it is just half of that of the steel, silicon nitrate, silicon carbide is even lower it is 3.2 gram per cc. The elastic modulus is higher than often it is higher than that of the steel.

For example, zirconia has a elastic modulus which is very comparable to steel around 210 depending on what is the doping content that varies between 140 to 210 and this elastic modulus the because of many similarities between zirconia and steel, the first paper which is published in nature on zirconia they call ceramic steel, the title of the paper was ceramic steel.

Fracture toughness of zirconia it is not that as bad as many of the ceramics, it is around 8 to 10. However, thermal conductivity is very poor, it is 2 watts per meter per Kelvin. So here I have not used many of the units like this should be watts per meter per Kelvin, this is GPa gigapascal, fracture toughness the unit is megapascal meter to the power 1/2, elastic modulus this unit is GPa gigapascal and density the unit is gram per cc okay or kg per meter cube whatever in that SI unit is kg per meter cube.

So all those things I have mentioned. Now if you move to polymers for example the polymers which are used like polyethylene for example high density polyethylene the thermal conductivity is even lower. So most of the polymer you see the thermal conductivity is less than 1 watt per meter per Kelvin and elastic modulus is even lower is orders of magnitude lower as I told you earlier.

However, density is also extremely low; it is like 1 to 2 gram per cc. So density wise polymers are much lighter than ceramics or metals. Elastic modulus wise it is also very low so that stress generation stress that will be generated at the contacting surface would be low and fractured toughness is also fairly low.

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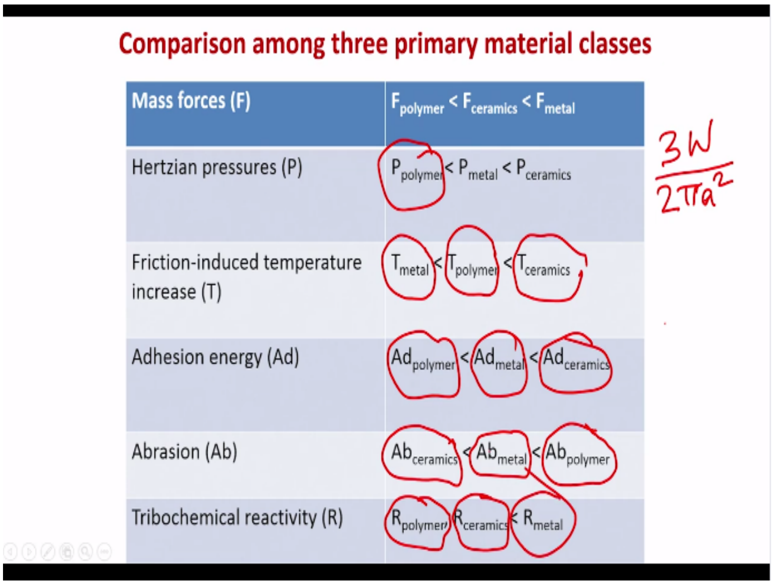

Now based on these considerations if you see that what would be the Hertzian contact pressures and so on, polymers Hertzian contact pressure would be fairly lower because Hertzian contact pressure if you remember it is 3W is the load/2 pi a square okay and there is friction induced temperature increase. In case of metals, the temperature increase will be lower compared to polymer.

Because polymer thermal conductivity is the lowest and followed by ceramics. Adhesion energy that means the two asperity contacts, they will come and they form an adhesive bonds so that would be lowest in case of polymers, it will be little higher in case of metals and ceramics would be the largest. Abrasion properties of ceramics would be higher because it has higher hardness.

And abrasion properties of metals would be intermediate and abrasion property would be polymers would be even lower. Tribochemical reactivity if it is R that means polymer the tribochemical reactions would be much more than metals than ceramics and then metals.

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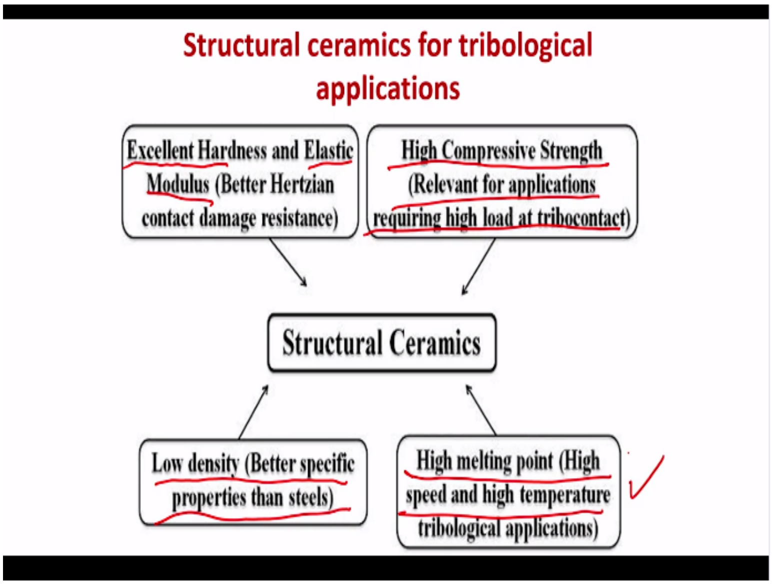

Okay so what are the different attributes particularly for ceramics which are very important for tribological applications? Now these different attributes are mentioned here, ceramics are one of the classes of materials which has excellent hardness and elastic modulus. What it means that it has a better Hertzian contact damage resistance. If you recall Hertzian contact mechanics is largely applicable to find out that what is the magnitude of the contact stresses.

And that is also high compressive strain okay that is relevant for applications requiring high load at the tribocontact. It has also low density that is better specific properties than steel and it has also high melting point, high speed and high temperature tribological applications.

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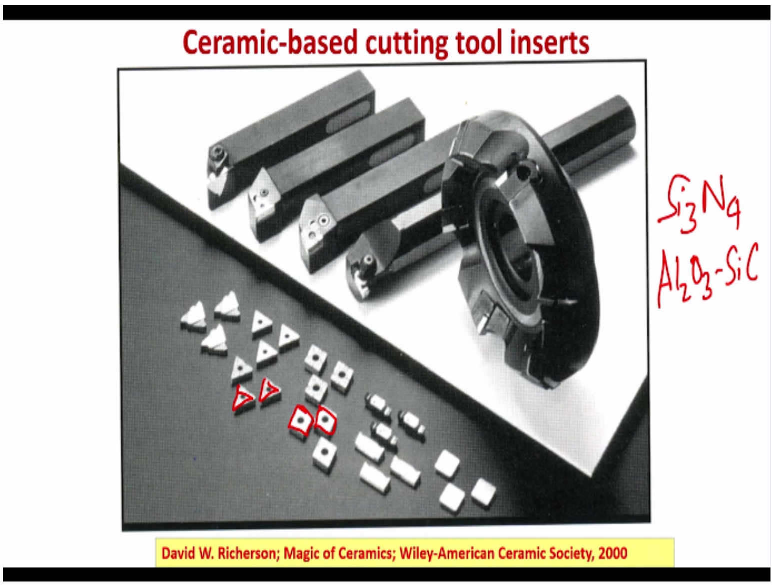

So what are the different ceramic-based cutting tools? The ceramic-based cutting tools as you see that these are mostly that made of the silicon nitride based cutting tools and sometimes people use also other ceramic compounds like alumina silicon carbide based composites. So you can see that cutting tools are of different shapes and sizes and is all these different shapes and sizes are very much useful for different ceramic-based cutting tool inserts.

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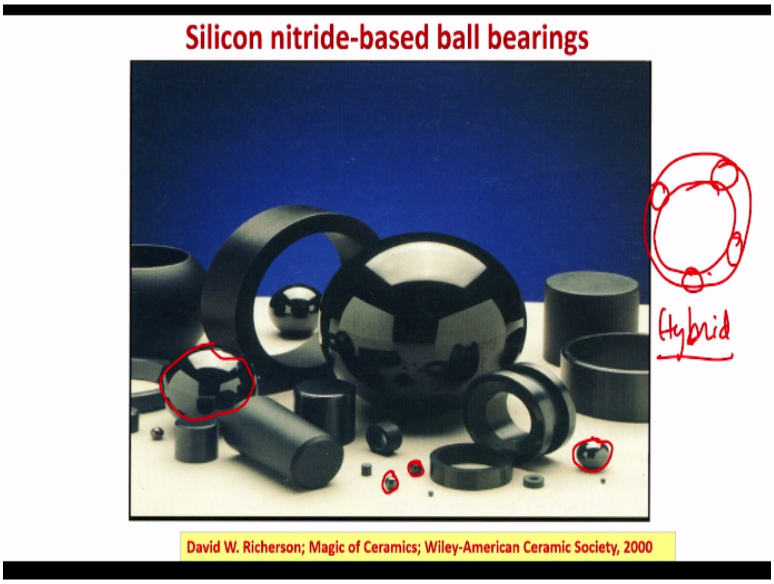

These are different examples of the other ceramic-based ball bearings for example silicon nitride and if you can see the silicon nitride balls are of different size right. It is available commercially in 5 to 10 millimeter to as high as 40 to 50 millimeter diameter and these bearing balls they have a longer life than corresponding metallic balls and also if you remember in one of the earlier lecture I said that it has a steel raceway.

And here the ceramic balls are being placed between two raceways and these will call it as hybrid bearing concept where ceramic balls are used in combination with a metallic raceways.

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Okay now coming to the other kind of ceramic materials which are used for tribological applications, so these are the examples of another ceramic materials that is silicon carbide. Now one of the point that I want to make about silicon carbide and silicon nitride is these materials if you look at their strength properties as a function of temperature, strain as a function of temperature.

And what you see that silicon carbide and silicon nitride there our room temperature strength is like this and their strength is maintained in both the silicon carbide or silicon nitride materials. So in most of the metals what happens the strength reduced with temperature because of the softening but this particular ceramics non-oxide ceramics the strength room temperature strength is maintained right up to high temperature and therefore this materials they are used for high temperature applications.

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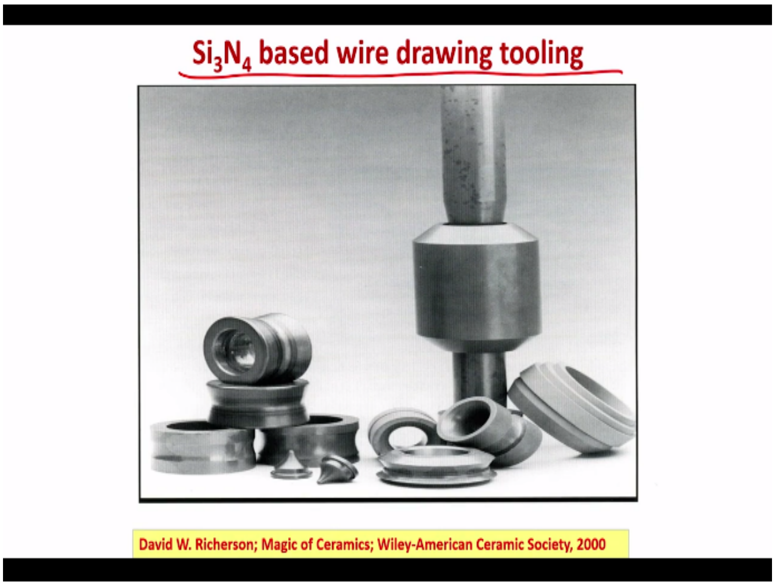

Okay what are the other application areas of ceramic materials like silicon nitride based wire drawing tooling. So wire drawing is one of the applications which are used, wire drawing is one of the process which uses tensile force to draw a wire from the die and as a result this wire drawing is very popular in various technological applications and these wires are very important that these wires have a very smooth surface.

And dimension and tolerance is maintained when you draw this wire. That is possible if and only if that wire drawing tooling for example wire drawing dies they have a very long life time. So if the wire drawing dies they were away then the final finish product that is the wire they will have very different diameter compared to the desired diameter of the wire.

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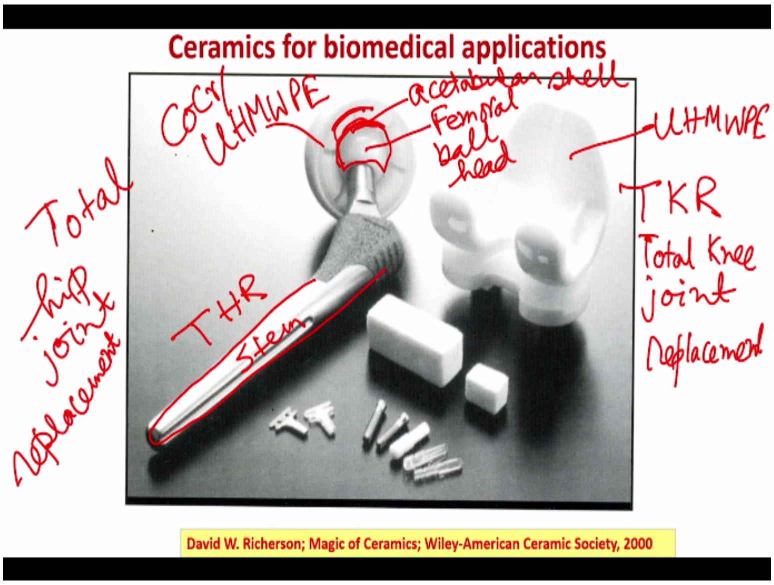

Ceramics are also used for biomedical applications. Now what you see here this is the total hip joint replacement okay. So this is called THR total hip joint replacement. This is called TKR total knee joint replacement and this is called total hip joint replacement. So this is your stem, this is your femoral ball head and this is your acetabular shell or acetabular socket okay.

Now here in this particular case this ball can be made of alumina or zirconia or the composite of the alumina and zirconia and these femoral ball head is being slided it is this acetabular shell here and this is the region that articulating surfaces what we call so these articulating surfaces they experience lot of wire and these wire particles have a very significant consequence on the inflammatory reactions in the body.

And if it gets worse that means that femoral ball head that wires very fast then the patient needs to undergo revision surgery and which is even painful and which also leads to high cost in this particular case. Total knee joint replacement also many patients who are suffering from osteoarthritis, they also often if the osteoarthritic pain or related pain is very large then they have to undergo total knee joint replacement particularly for the elderly patients.

Again, total knee joint replacement often people use ultra-high-molecular-weight-polyethylene or their composites and this particular acetabular shell either it can be used as a metallic shell like cobalt chrome alloy or it can be used for this ultra-high-molecular-weight-polyethylene and either case what you see here that this wire is a main problem and which if it is very worse then it can lead to it requires the revision surgery.

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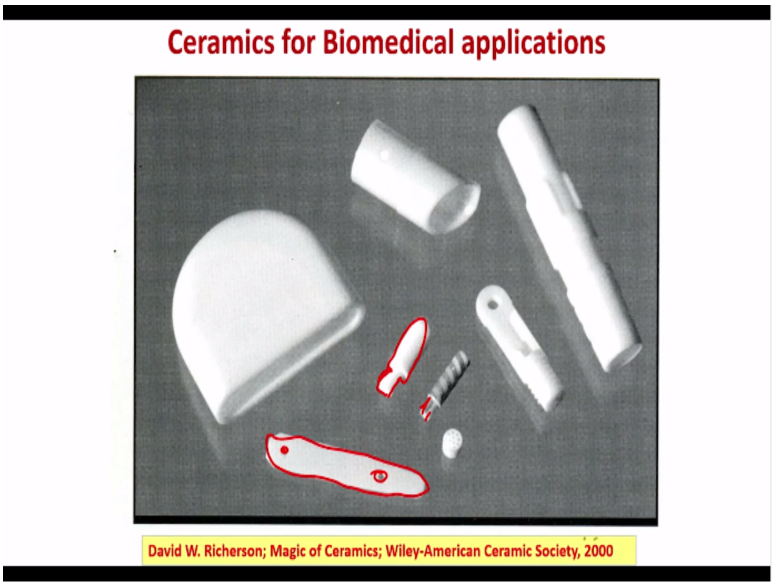

There are several other examples where ceramics can be used for biomedical applications for example this is a plate of the ceramics and you can see these are the two holes on the ceramic plates through which the screws can be tightened to the neighboring bone area. So also ceramics can be used for dental replacement like you know if you have a single piece ceramic implant as opposed to two piece dental implant which is made up of the alumina, so these are also used in the dental implant applications.

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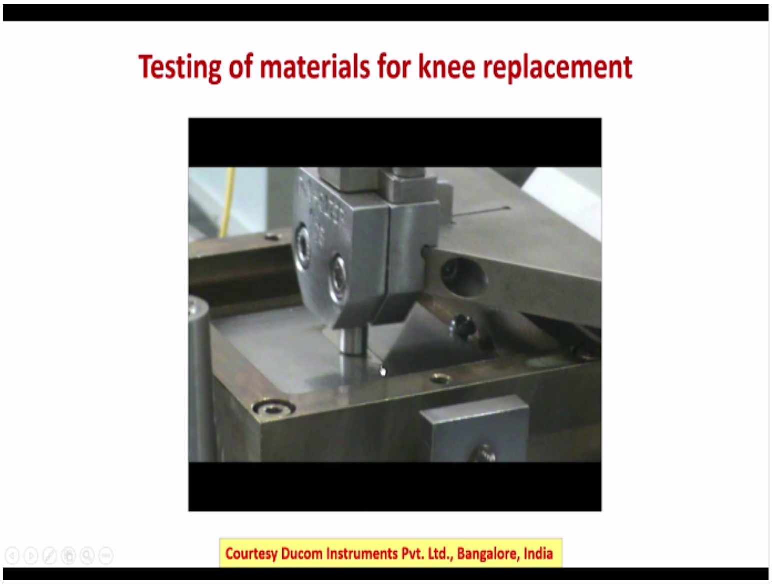

This is one of the examples that you know that where the knee replacement this knee replacement operation or the wear involved in the knee replacement can be simulated in the laboratory scale equipments and this is also commercially available and this laboratory scale equipments they can simulate the exact gait cycle of the knee. Similarly, other biotribometers they can be used to simulate the exact hip articulating motion.

And what you call is that hip simulator. Similarly, there is an equipment called knee simulator where the articulating motion of the knee can be simulated in an equipment.

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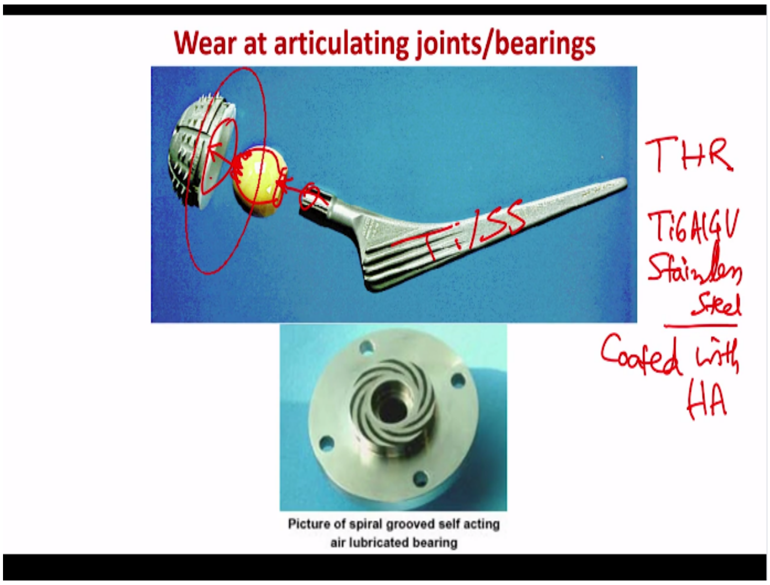

This is much more closer view of this that total hip replacement that I have mentioned before so you can see this is a titanium stem or stainless steel stem often to improve their properties biological properties or biocompatibility. This Ti6Al4V stem or stainless steel stem that is low nitrogen stainless steel stem, they are coated with hydroxyapatite and these particular area stem part which will go and get fitted into the femoral head and if you see this particular femoral head they have a particular spherical like shape.

But it is not fully spherical and this spherical shape gets fitted into the acetabular socket. So this is the region whatever asperities are there and in this acetabular shell and socket region whatever asperities there they will interact and they will contribute to friction and wear. So therefore it is very important for these materials to be extremely wear resistant. However, there is a chance that physiological fluid.

Because everything you will be all these artificial hip replacement, artificial hip assembly has to be placed in a patient's body. So you have a physiological fluid which can partly act as a lubricant for this total hip replacement but this lubrication efficiency of this physiological fluid is certainly not as effective as like a commercial lubricant which are used in various machines.

So this bottom one is an example of a spiral grooved self-acting air lubricated bearing so this compressed air also can act as a lubricant not only as well but also compressed air can be used as a lubricant.

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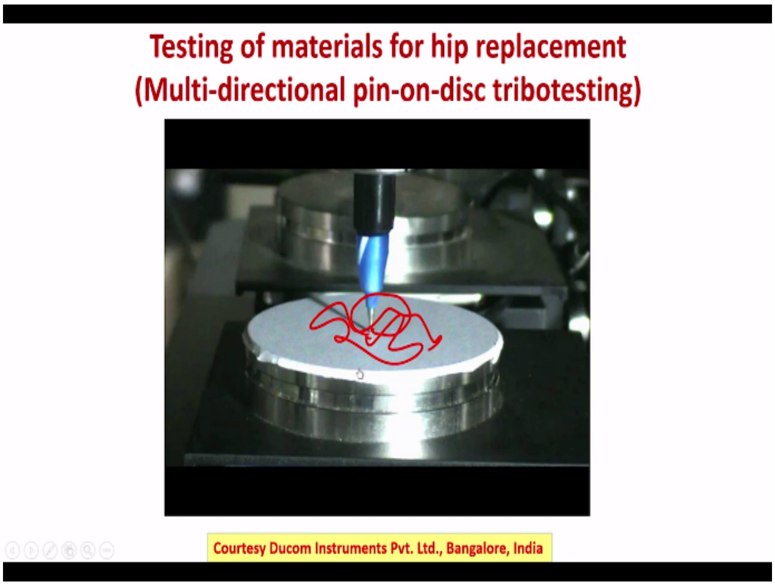

Okay so this is in the multidirectional pin-on-disc kind of testing and if you see this multi-directional pin-on-disc testing that means these machines will operate in different directions like pin in this particular motion. So essentially this pin will not rotate like this but pin will go in a zigzag motion and this zigzag motion essentially will simulate some of the biological phenomena at the articulating joints.

And therefore this kind of machines not the conventional pin-on-disc tribotesting that will be very useful for most of the performance limiting assessment. Now this performance limiting assessment is very important like whether it is a lifetime extension or it will cause reduced life. These things can be evaluated using this kind of tribometer.

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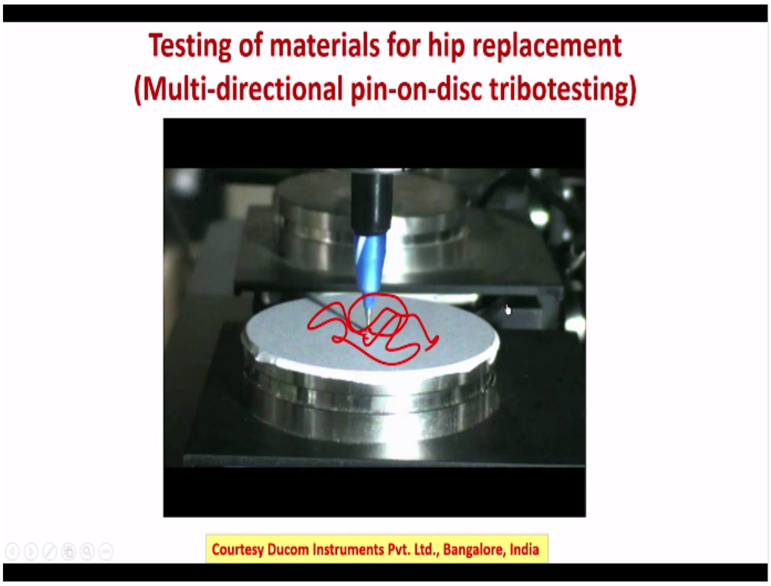

This is also another tribometer which is used for testing of the hip replacement, this is called again multi-directional pin-on-disc tribotesting and this is also another test of, these are the (()) (25:45) equipments so which is not very used very extensively but it is certain in the developmental stage and with the availability of this particular machines, it is expected that these wear and friction phenomena which is taking place at the articulating surfaces can be better understood and can be better quantified in laboratory experiments.

So what we have done in last lectures, we now have a broad understanding as how this we have a broad understanding I would say on the very fundamentals of friction and wear.

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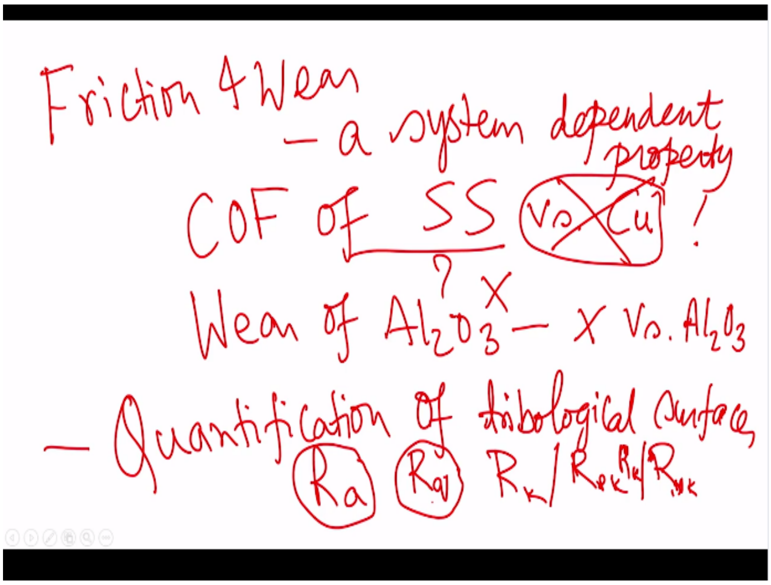

So if I recall that first thing we learnt is this friction and wear is a system dependent property right. So in other words, friction is not a material property. Similarly, wear is not a material property. So I often made the statement that if somebody would ask you what is the coefficient of friction of stainless steel, there is no answer, there is no unique answer but then if somebody would ask you what is the coefficient of friction of stainless steel versus copper, then you can give an answer okay.

So without this versus copper, this question does not have any answer simply because there is nothing like friction of stainless steel because fiction of stainless steel against what, that is very important okay. Similarly, if somebody would ask you wear of alumina, wear of alumina there is no unique answer of wear of alumina because again you have to say that wear of alumina versus alumina then it is called self-mated alumina or wear of alumina again zirconia then in that case it is a dissimilar couple then what is a wear rate?

So these are the very basic things that we learnt in the first one or two lectures. Then, we have quantified how that quantification of the tribological surfaces and what is the thing that we learnt there, we learnt that what are the parameters Ra and we have also argued that although the two surfaces can have the same Ra but they can have different Rq value. Ra is nothing but average surface roughness, Rq is nothing but RMS surface roughness, root mean square surface roughness.

So the two surfaces may appear to have identical Ra values but they may have a different Rq values and there is something called Rk, Rpk, R peak value and Rvk. So Rk, Rpk, Rvk and then often they are ready ratio of Rk/Rpk Rk/Rvk that ratio also changes.

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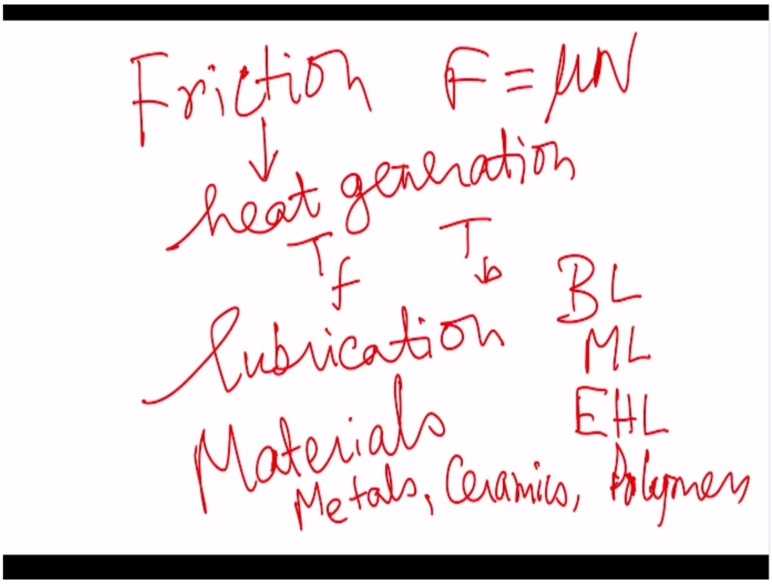

The second thing that we have learnt that what is the mechanism of friction and what are the loss of friction and there we have learnt that frictional force is nothing but mu N. Then, what are the different characteristics of the friction and then we say that this friction leads to heat generation right and how to quantify the two different characteristic temperatures, one is called flash temperature and one is called bulk temperature.

And then next we learnt about lubrication. In the lubrication, we learnt that what is the purpose of lubrication and then we have seen that what are the different lubrication design like BL bounded lubrication, ML mixed lubrication, EHL elastohydrodynamic lubrication and then we have seen what are the different materials, which is lastly used for tribological applications.

And this will constitute metals, ceramics, polymers and their composites and we will see some of the case studies later that where their composites are actually used and they are being developed as a new generation wear resistant materials. Thank you.