Introduction to Biomaterials

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Module No. # 01
Lecture No. # 02
Manufacturing and Properties of metals, ceramics, polymers and composites

In this lecture, I will deal with fundamentals of manufacturing and mechanical or physical properties of materials. So, these fundamentals are necessary to understand some of the future lectures.

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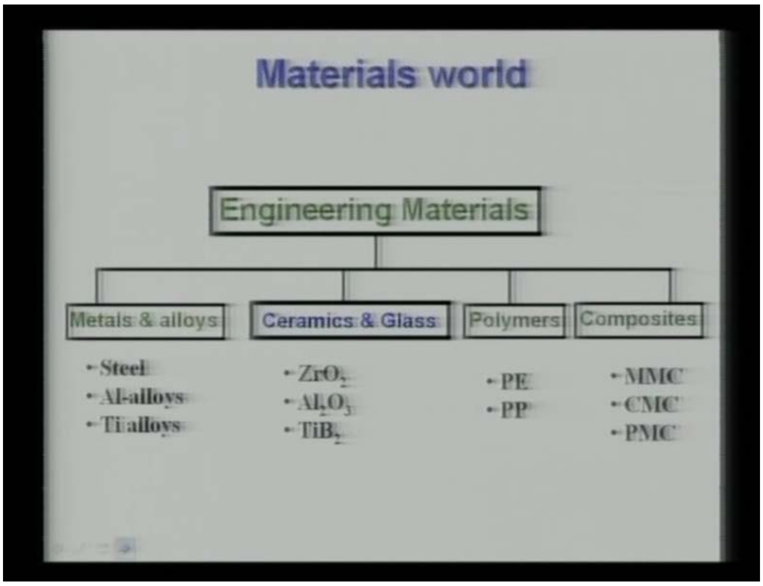

So, here we need to recall, that you know engineering materials can be classified into three primary classes, that is one is metals and alloys, second one is the ceramics and glasses and third one is the polymers and then fourth one, that is the composites which, I call them derived material class, because poly composites are essentially mixture of who of three primary material classes, that is metals and ceramics or ceramics of polymers and polymers of metals.

And accordingly, they are termed as M M C, C M C and P M C under each category of the primary materials like metal, ceramics and glasses, I have given some examples, like steel is primarily used as biomaterials in India, in Indian scenario because steel is relatively less expensive, where the titanium alloys like which is used as the stem of the total heat replacement which is rather costly, because titanium itself is quite costly compare to steel.

Now, among the ceramics and glasses, so zirconia and alumina, they are two competing materials which are potentially used in the femoral ball head applications, polyethylene is also used as the ace tabular cup in the total heat replacement, so these are the examples of the biomaterials from different primary material classes, that are currently being used.

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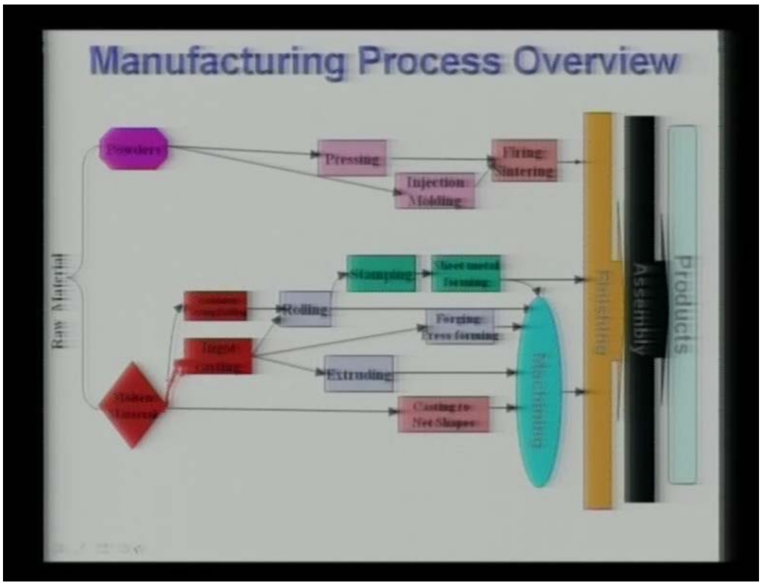

Now, some idea about the manufacturing processes, like how this materials are manufactured, mostly in this slide I will show you, that typical manufacture routes which are employed for the manufacturing of metals and ceramics. Now first, let us go through metals how it is done, so you start with the molten metal, then it this molten metal can be cost into a particular in guard in a particular shape and subsequently this in guard can be rolled to make it a plate and this plate can be directly used like you know in the plates like used in the different biometrical applications, it can be mentioned as required and finally, its finishing and going to the products as the biomaterial products.

Now, there is other way of making this same plate that is the continuous casting or continuous rolling route, so continuous casting means, this molten metal will be poured into a heygen and mold and it is being continuously cast to the continuous caster machine. And then, depending on the thickness of the roll product that we want; so these continuous cast product can be subsequently rolled, to make it as desired thickness as possible and subsequently, they can be go to the finishing stage and assembly stage.

Now, same in guard can be cast, can be excluded to make a rod like, you know various biometrical applications you require product of different shape and different sizes, for example, it can be used as plates, it can be used as rods, it can be used as screws; so depending on the end application or end product, that you want you can particularly use or you can adopt a particular sequence of applications, sequence of processes in during the manufacturing of this materials.

Now, the other way is that powder, so powders are typically used for ceramics or polymer based materials, so this powder based manufacturing routes are essentially applicable for ceramics and most ceramics are polymer based materials. Now, you start with the fine powders, then you can press it a particular shape which is called green body. Now, this green body you can subsequently quire or filter to make a particular product.

And in this process, you can either get a very simple shaped product like cylindrical size product or you can get a complex shaped product and for that complex shaped product, during the pressing itself you can use the seep, what is called cold isostatic pressing. Now various polymeric based materials, you start with the powder, then you can do injection molding or extrusion and subsequently you can fade it, to remove the binder from this polymeric product and then it can go through the finishing stage and finally, product stage.

So, this particular route as I said is particularly useful for ceramics or polymers and these particular routes like molten metal’s these are particularly useful metals and alloys, so more specific description of individual routes will be given, when I will discuss individual class of biomaterials like bimetallic alloys or bio-ceramics or bio-polymers.

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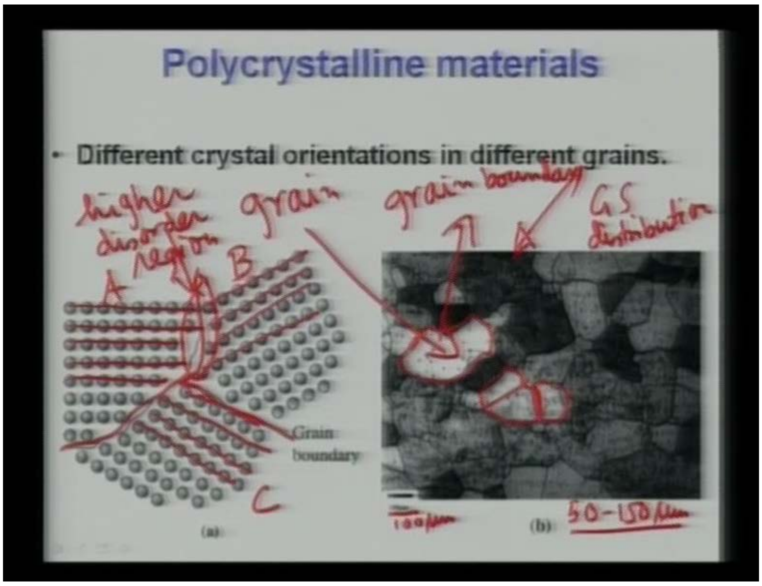

Now, before going to further, let us first understand that, you know that how typically microstructure looks like, because this course of biomaterial is is equally relevant from people or for students from different disciplines, they are for a primary understanding of how this microstructure looks like, that is important and how to characterize the microstructure.

Now, this is a typical microstructure, that one can observe for typical qualities and materials, now in this microstructure what you can see, that there are individual area which is demarcated from other area by some boundary, now this boundary is called grain boundary and the area enclose microstructure region enclose by the grain boundary this is called grain.

Now, left hand side image actually tells you that, inside the grain, so this is your grain boundary the way I am sketching it here and this is inside is your part of a grain, so in each grain the the lattice planes at they are and along this lattice planes atoms are arranged in particular orientation, grain A to grain B, you see that orientation of the atoms also subsequently changes. Now when you go from grain B to grain C again across the grain boundary your orientation of the atoms are also changing, essentially what it means, that grain boundary is the is the area where the orientation of the atomic planes changes from a particular orientation to a completely different orientation.

So, this is the area grain boundary, is the area of the higher disorder region, so this this brief understanding is is required because, later on later on I will mention about the grains and grain boundaries very often to describe the microstructure of different materials.

Now, second important thing these microstructure to understand, that this particular scale bodies around hundred microns, so from this scale bar, one can understand, what are the typical size of this grains and this typical size, if you take a particular diameter of this grain, so it will be roughly 1.5 times this scale bar. So, it will be rightly 150 micron.

However we should also notice here, that this grain size is not a fixed value, there is a variation of this grain size across this microstructure, so there is a term called grain size distribution is often used to characterize the microstructure or in other words, you can say roughly from the visual look of this microstructure, that grain size here typically varies between 50 to 150 micron and if you say that, then you will be competing the description of these kind of microstructure.

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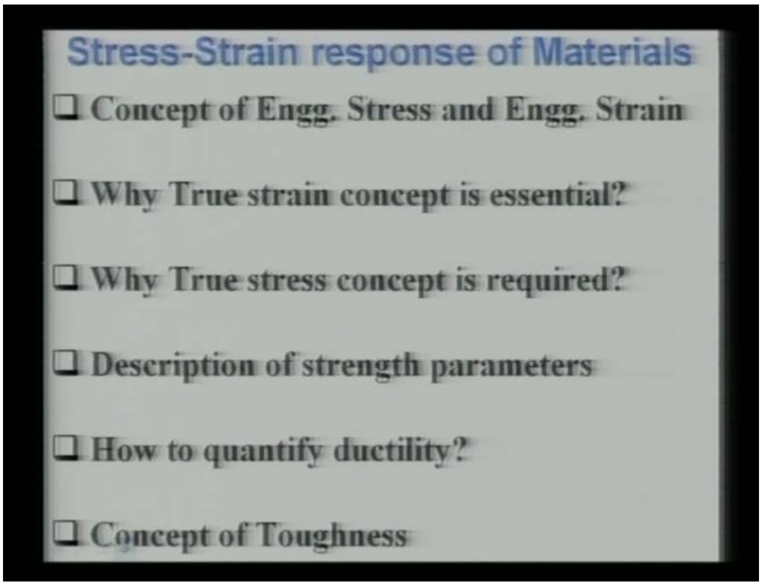

So, this is in general brief, that how the microstructure looks like and how one can characterize this microstructure in scientific terms; now in the next few slides I will go through quickly, about the concept of engineering stress and engineering strain, so these particular set of slides which I will be showing in next several minutes, that are essential to understand the typical mechanical behavior or mechanical properties of materials.

Now, first one will be the concept of engineering stress, engineering strain and how this true strain concept is essential and true strain concept is also require, now what are the description of the strength parameters; now, how the strength properties load bearing capability of materials, materials can be described, how to quantify ductility and what is the concept of toughness, so all these concepts will be discussed one by one.

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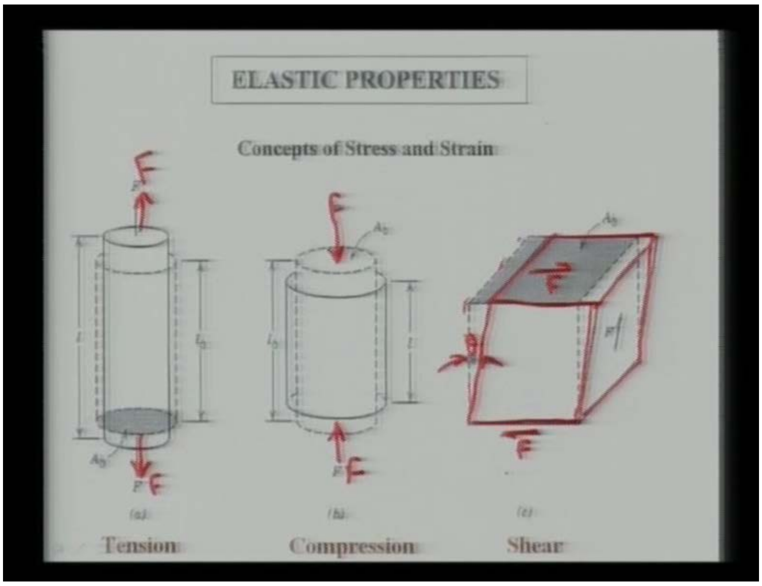

So, first let us start with the description of typical stress and strain. So, left hand side what you can see this is cylindrical specimen and this cylindrical specimen is cooled in tension, so this is the simplistic description of how a tensile force is applied to a cylindrical specimen and as a result the cylinder will increase its length and decrease in the cross section, an increase in length will be incomence through the decrease in cross section upto a certain point during tense and tail, now those details I will describe it later.

Now, let us look at the middle slide, here a cylindrical specimen is being compressed by a force air and as a result it keeps on decreasing in height and keeps on increasing in the diameter, again this is the most simplistic description of the compression force. Now third one is that, the shear stress these dotted lines is the original position of a cube, for example, and in this two opposite phase if you apply equal amount of force which force amount is air, then after you apply this force on the two opposite phases this bold lines essentially essentially indicates the new state after the application of the stress.

What you can see that, there is a kind of angular distortion of some phases by the angle theta and this is a typical description of the shear strain and here again surface area of the top phase and bottom phase remain same. So, from this slide it is clear to you there are essentially there are three types of spaces, this is again three primary types of spaces, one is called tension one is called compression and one is called shear and each each type of force they apply in a characteristically different manner and that, has a typically three different type of effect on a material shape or material size.

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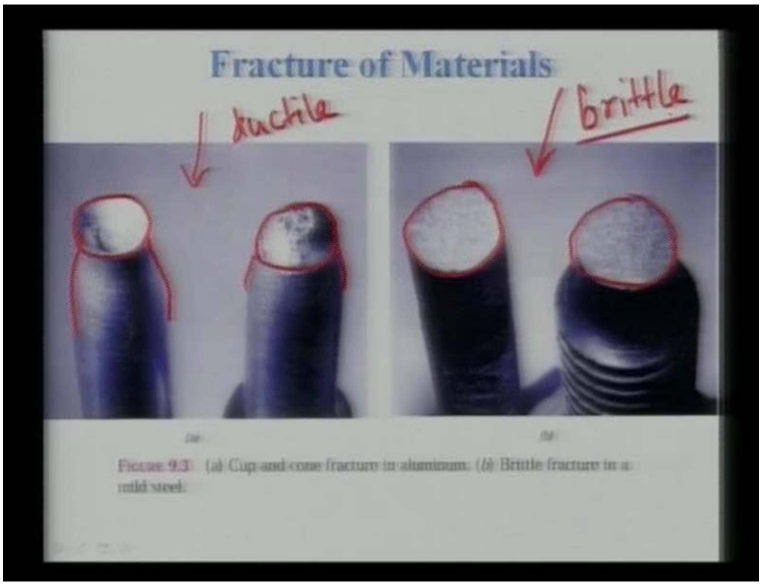

Now, this shows, that you know is a typical metallic materials in you do the test at a particular temperature and if you do a test at a craginic level, how these two behaviors can be different, now this one is a typical ductile behavior, why I am saying typical ductile behavior; so this is the two parts of a long cylinder which is being cooled in tension and what you see here, you look at this area and you look at this area, in these two area prior to fracture the material as experienced extensive deformation, because you can see this diameter of the cylindrical specimen here, that shows extensive contraction prior to fracture and this is called in metallurgical language called cup and cone type of fracture.

Now, if you look at this particular fracture behavior, that there is no such contraction in the diameter prior to fracture and this kind of fracture is known as brittle fracture; now this brittle fracture is typically notice for a metals below the DBT, DBT means Ductile to

Brittle Transition temperature, if you test any metal below the ductile to brittle transition temperature, this metal will behave mold like a brittle material.

Similar observation are often found while testing, most of the ceramics, because ceramics are essentially brittle as I have explained in the last lecture, so essentially from this view graph, you can clearly distinguish between ductile and brittle fracture, in case of the ductile fracture, you have large deformation prior to fracture, in case of brittle fracture the material simply is broken to two pieces without experiencing or without undergoing much deformation prior to fracture.

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Now, why mechanical properties are important, here determine a material's behavior when subjected to a mechanical stresses and this properties include elastic modulus ductility and hardness and various measures of strength, now therefore, this mechanical properties determination or mechanical testing is important, now mechanical properties desirable to designer, that is who design different materials is high strength and usually make manufacturing more difficult, because if you take a very high strength material then to process the material to a particular shape becomes more and more difficult, because you require very large capacity rolling phase or porting phase to deform that material because the material itself has very high strength. So, whatever desirable to a designer many times make difficult for a mechanical engineer or material scientist to process, that material because manufacturing becomes more difficult for high strength material.

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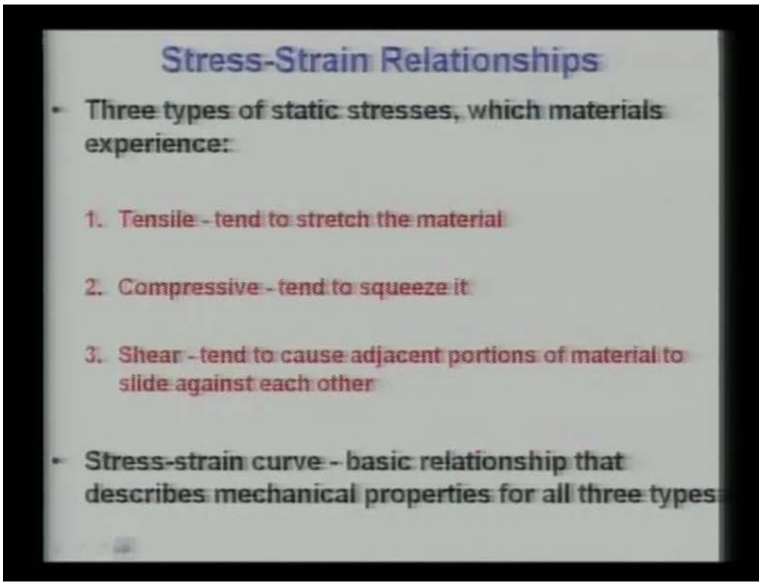

So, t his point is important, because these are like some other finite details, for a student or researcher should understand or should take a note of it, this is just a brief description what I have just mention a few minutes ago, tensile essentially means: tend to stretch the material, compressive means: tend to squeeze it.

So, that is the simplistic description shear means: tend to cause adjacent portions of materials to slide against each other, so these are like three different types of static stresses which materials experience, now in few slides more I will be describing the stress and curve and this stress and curve essentially describe the basic mechanical properties for all the three different types of stresses, that I have mention in the above.

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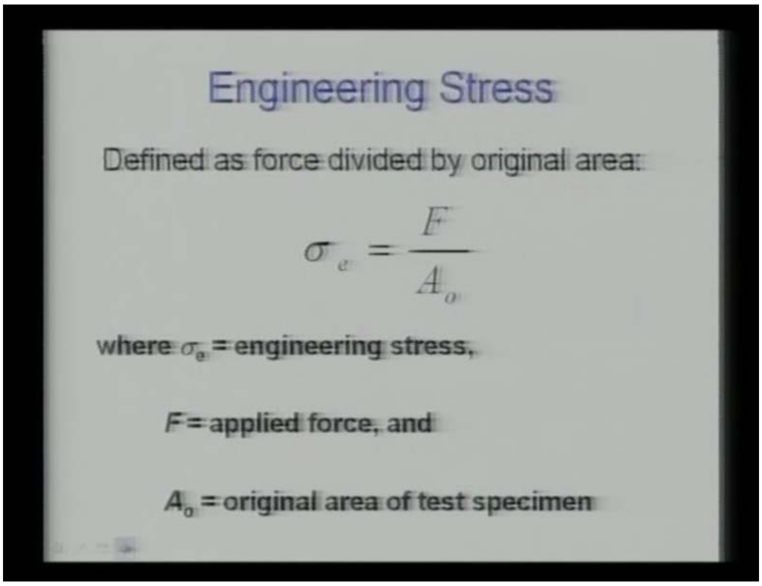

Now, first understand, what is called by engineering stress? Engineering stress simply means the force divided by initial or original area of the test specimen; so this is the original cross sectional area, so initial cross sectional area of the case specimen and this is a simplistic description or definition of the engineering strain.

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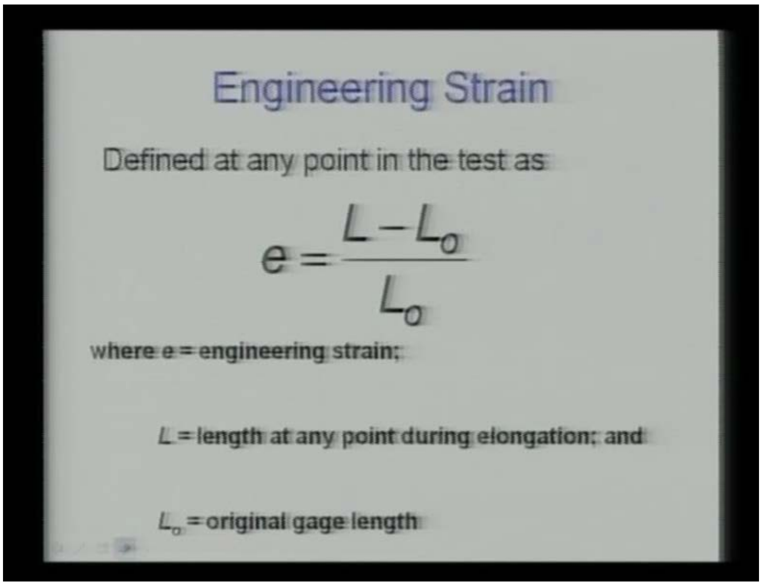

Similarly, engineering strain means, that is the length at any point during elongation minus original length or initial length divided by the initial length, so that is the is the length increment divided by the initial length, that is defined as the engineering strain.

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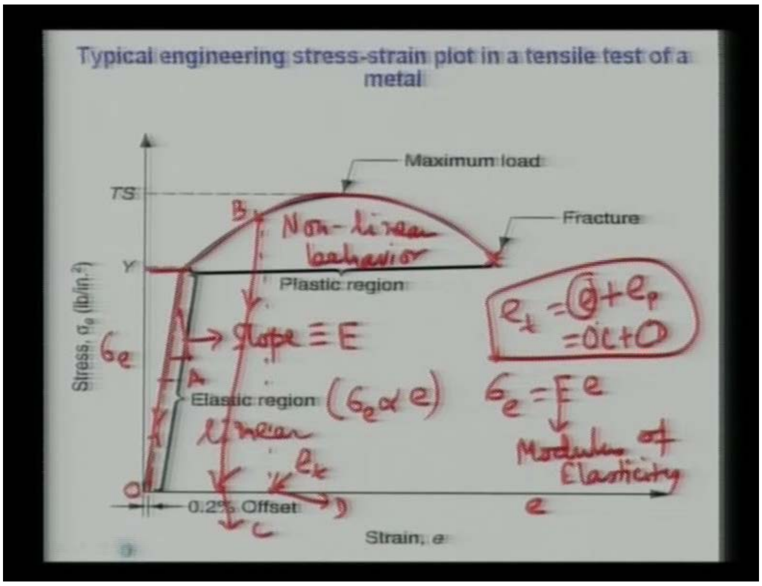

Now, this is a typical stress tensor of a ductile metal and what you see in this typical stress tensor, that initially you have the elastic region and in this elastic region this is the stress, that is the sigma e is the engineering stress and d is the engineering strain, so in this region sigma e is proportional to small e and this proportionality constant known as the elastic modulus. So, from the slope of this curve you can create essentially elastic modulus of a metal, so essentially what it means, it means suppose you start with a point 0, you go to a point A. For example, now if from this from this A, if you load it to the point A and if you release the load at the point A, then it will come back to the original position.

So, this is the this is the meaning of the elasticity, elasticity means it is just like a you know elastic rubber or something you stretch it, that the moment you release the stress it comes back to the original position; the same thing it happens to a metal also like you up to this particular point Y, at any point if you load it and if you unload it the metal it comes back to the original position and in this region sigma e is equal to e times small e that is the elastic modulus of elasticity, so this is known as modulus of elasticity or elastic modulus.

Now the major thing, that happens when a metal undergoes from elastic region to plastic region and in this plastic region what we called is a non-linear behavior, so this region is called linear behavior and this region is called non-linear behavior and this non-linear behavior what you see here, that this is called the plastic region; why this is called plastic region, because here if you go to for example, a point B and if you unload it the material will come back like that, it will not follow the original path of loading.

So, it will come back the unloading will take place in a completely different path and in this region if you want to find out that, what is the elastic strain and what is the plastic strain, suppose this is your total strain epsilon t or e t; now e t is equal to e, that is the simple e, that is the elastic strain and e p, that is the plastic strain and how to find out, that what is the plastic strain, because these when you reload when you unload it it comes back to for example, the point C and this is your point D.

So, that elastic strain e is nothing, but O C and plastic strain is nothing, but C D, so that is the total strain, that a material load experience in the plastic region. Now here, from this view graph you can understand that what happens to a cylindrical specimen when it is being cooled in tension.

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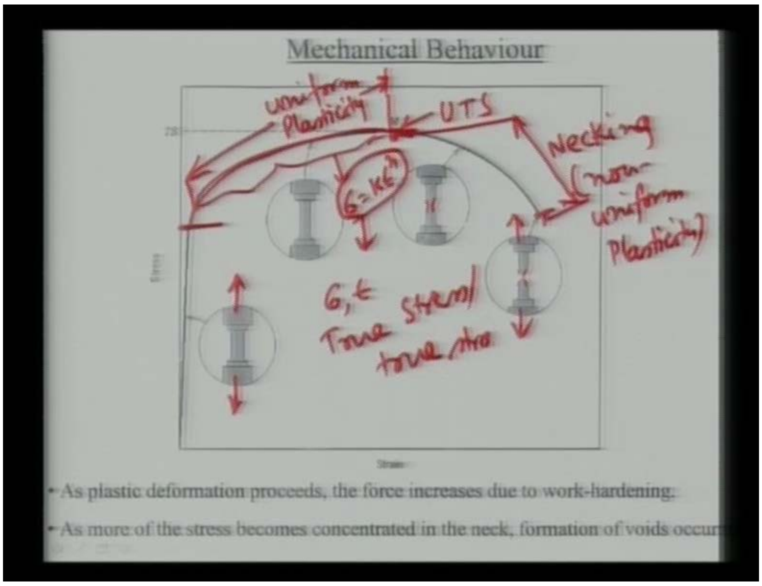

Now, when it is being cooled in tension, here at this non-elastic non-linear behavior of plastic region, what you see this material will keep on extending in length first, but beyond this point M what is called as that UTS that is the ultimate tensile strength region, that decrease in a cross sectional area is faster than the increase in the length.

I repeat beyond the ultimate tensile strength or upto the point of fracture decrease in the cross sectional area is much faster than the increase in length; that means, that the material will confront at this cross sectional area faster than the length increment, that the material will experience and as a result what will happen upto a point F this material will not be able to bear the load for that, any further and it will cause the total fracture of the material.

So, this region actually known as the necking region and necking means this is like a non uniform plasticity and this region to this region this region is called uniform plastic behavior.

Now, you know that, how you can characterize the entire stress (( )) you have the elastic part up to this point, then your non uniform and non and the non-linear elasticity, non-linear plasticity behavior starts and in this non-linear plasticity up to the point m then your necking starts the material goes to fracture and in this region of non-linear behavior one can roughly write that sigma is equal to k epsilon to the power n. But where sigma and epsilon are the true stress and true strain values of the material; so I will come back to this true stress true strain concept now, so this thing I have already mentioned that is the e modulus of elasticity.

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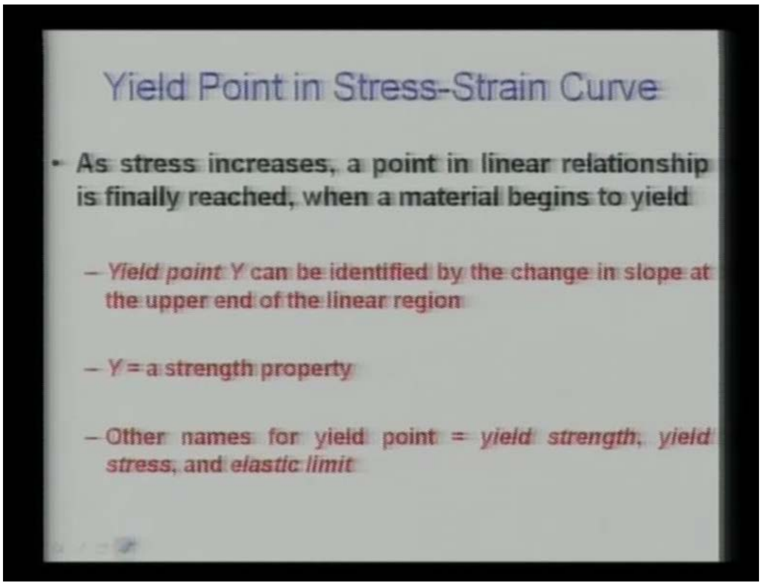

Now, yield point y that can be identified by the change in the slope, at the upper end of the linear region, so that one also you have seen that, how to identify the yield strength of a material.

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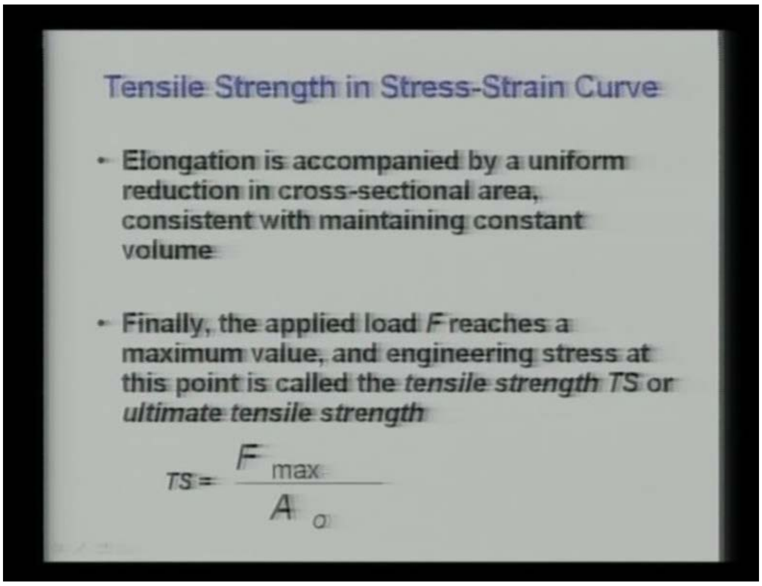

So, TS or final ultimate tensile strength what I have said that UTS is nothing, but total F max divided by A naught, now if you go back to the slide; so how to find out this ultimate tensile strength, so what is the load here, so this is the load, suppose this is the load F max and your original area of cross section is A naught, so from that, you can find out that what the ultimate tensile strength of this material.

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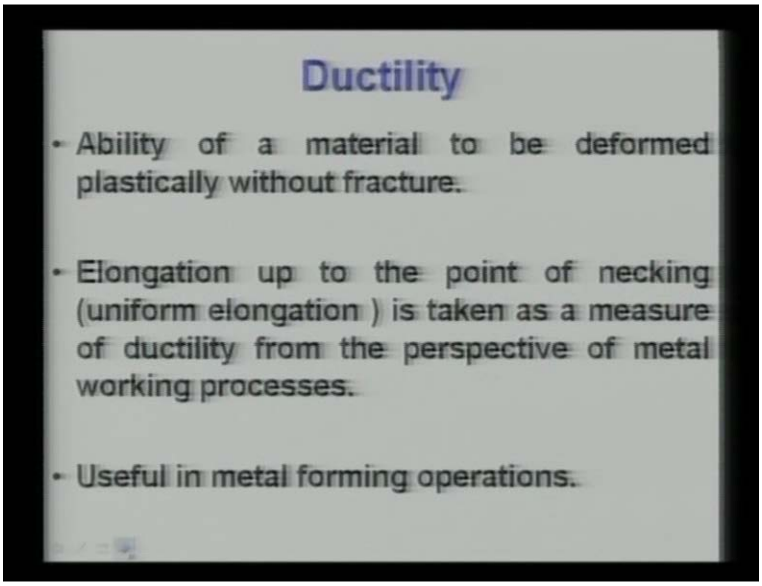

Now, Ductility Ductility is that ability of the material to be deform plastically without fracture, so that means, elongation up to the point of necking is taken as a measure of ductility from the perspective of metal working processes. Now, if you go back to this particular slide, now you would be able to reconcile very clearly that, what is meant by ductility, what is the definition it says that this region what is the total strain up to the point of necking, so this is your point of necking here, so this is the start of the necking so that means, up to this point the total strain, that the material can experience that is called as a ductility property of a material and typically fracture toughness or toughness is the total area under the stress-strain curve. So, this total area of under the stress-strain curve that is defined as the toughness of the material, so there are two terms here, one is the toughness and one is the resilience, now resilience is the area under the curve up to the elastic part and toughness is the area of the curve up to the total area of the curve up to the plastic part.

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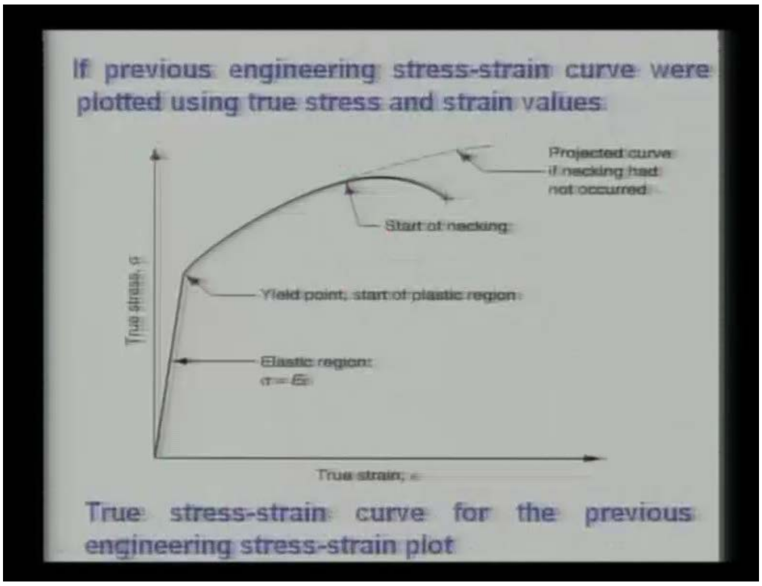

Now, coming to the concept of this true stress true strain curve, now what you have seen here that in the engineering stress-strain curve, that is essentially based on the initial original cross sectional area, but true stress true strain curve is actually based on the instantaneous cross sectional area and this instantaneous cross sectional area if you look at this is the dotted line here, this is the true stress true strain curve and this projected curve if necking had not occurred and this is the start of the necking. Now if previous engineering curve were plotted in the true stress true strain curve then, it will give you curve like this and again you have this elastic region, you have the non-linear behavior which is called plasticity and then it goes to fracture of the material.

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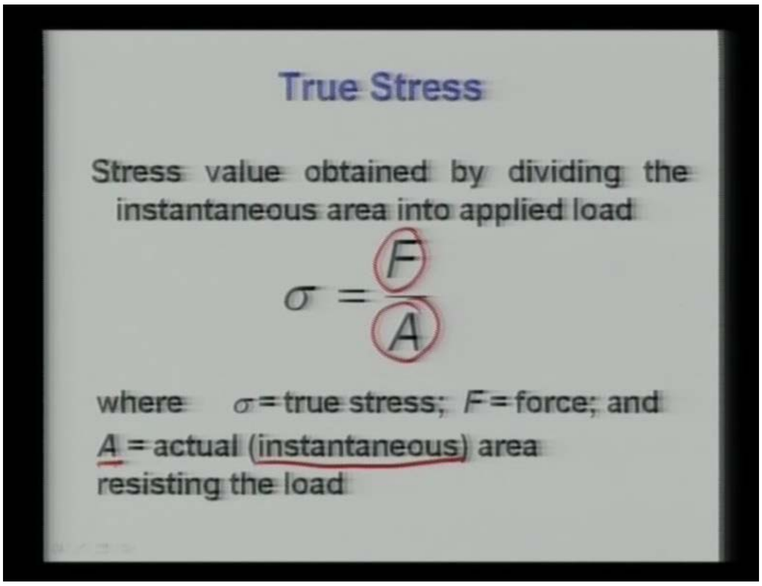

Now, how you define the true stress? True stress is again essentially force by instantaneous cross sectional area, instantaneous means at any given point of time, what is the cross sectional area of the metal it specimen, that is known as the true stress of the material and what is called true strain? True strain is again, that it is a very standard formula that is true strain is nothing, but l n L by L naught and what is the L this L is again the instantaneous length of the specimen, so L is the instantaneous length of the specimen and L naught is the original length of the specimen.

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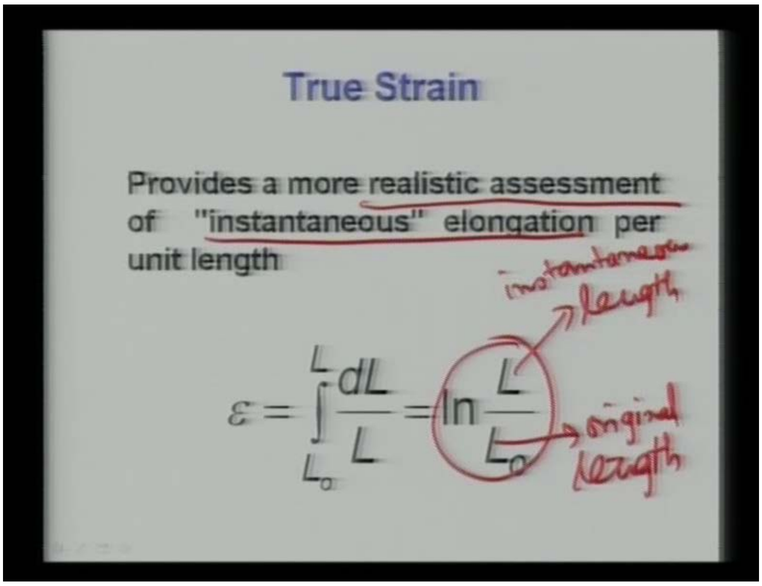

So, load natural of the ratio of the instantaneous length to the original length that can be defined as the true strain and because it provides a more realistic assessment of the instantaneous elongation, that is the reason why true strain is typically use.

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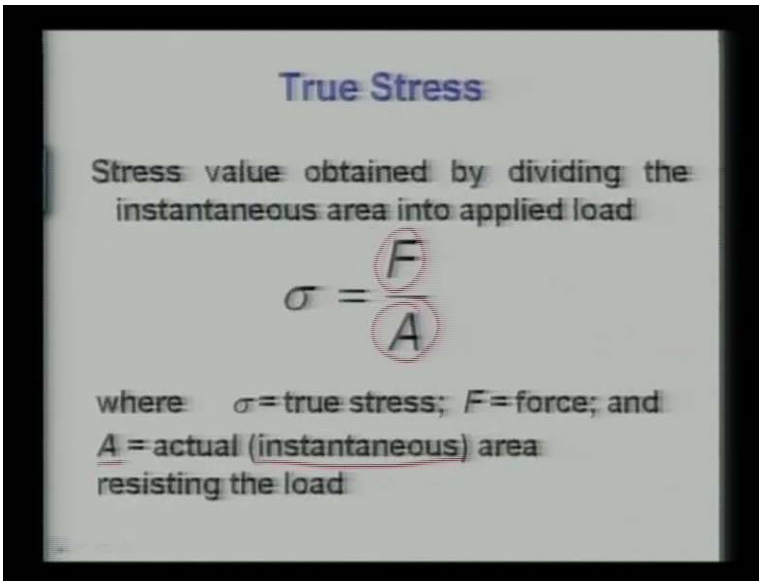

So, I go back to the true stress, true stress is again the ratio of the force divided by the instantaneous cross sectional area that is known as the true stress.

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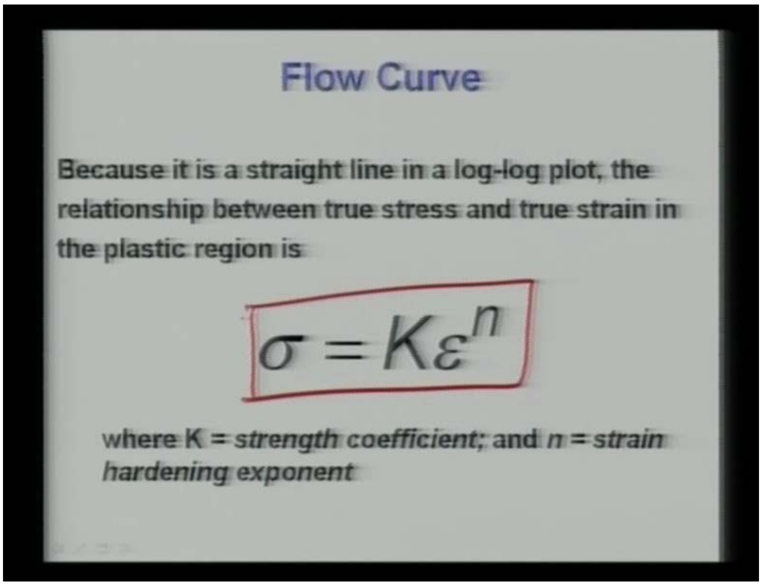

Now flow curve, now if you look at this uniform elongation up to the point of necking as I said here, the true stress and true strain they follow sigma is equal to K epsilon to the power n this kind of relationship. Now, what is n? n is typically strain hardening coefficient and typically it is around .1 to .5, so this is the value of n, that typically had K is the strain coefficient, epsilon is the true strain, sigma is the true stress.

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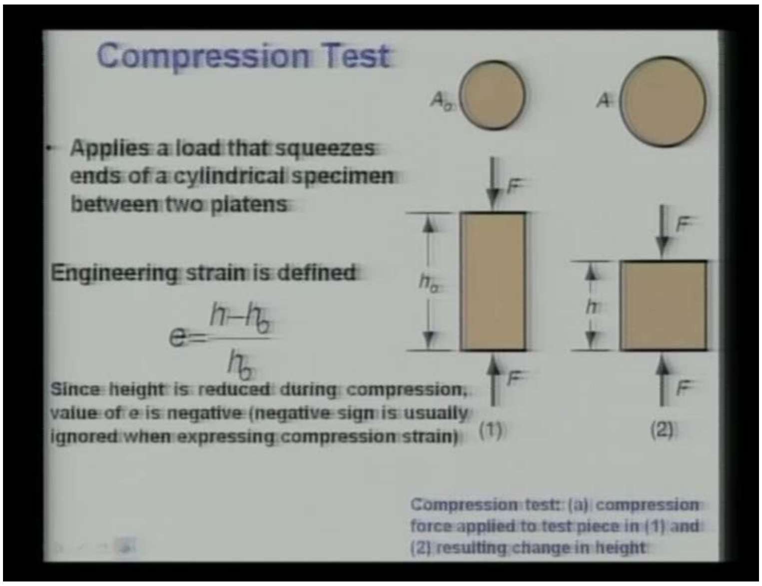

Now, coming to the compression test, now compression test as I mentioned earlier, that it essentially means that, you are actually squeezing with the application of some force from the both the ends and equal amount of force is applied from both the ends and this is the initial initial state of the sample, this is the final state of the sample, what you see that is cross sectional area increases.

So, that increases to A from A naught to A and their h naught actually decreases to h and that is as a result of the compression test and here engineering strain is defined as follows, that is the height decrement defer is that original height. So, that is h minus h naught, so h is the initial, e final height, h naught is the original height by h naught that is how engineering strain is defined; now how this engineering stress-strain curve that looks like during the compression test now looks like initially it goes through the linear region.

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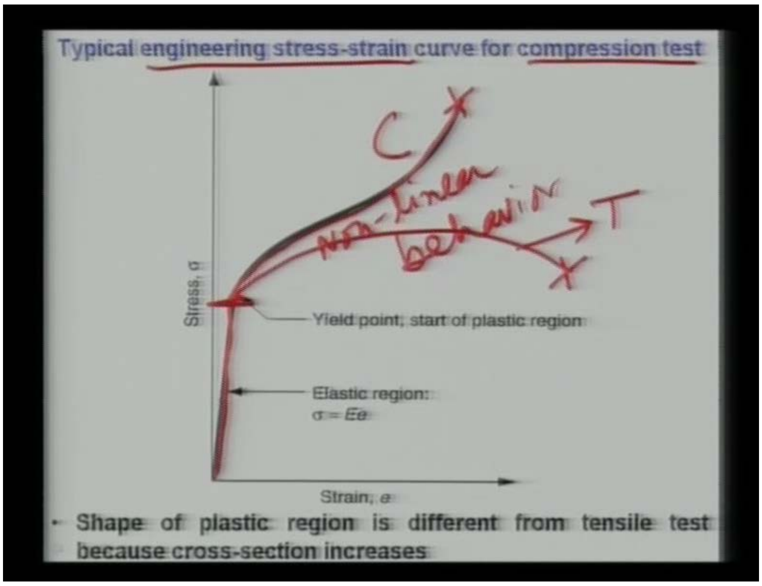

So, up to this point the material is linear, now from this point onwards it goes to the non-linear behavior and goes to fracture and this is the non-linear part and here what you can see, that it is largely different from what you have seen in case of the metals. So, for compression behavior it goes through the nonlinearity screw, but it keeps on increasing in a non-linear fashion and then it goes to the fracture region.

In case of that tensile test, it goes through this kind of behavior then it goes to fracture, so, this is for tension T and this is for compression C, you can clearly see for the same metal it behaves differently, when it spaced when it is swashed in tension, compare to when it is squeezed in compression.

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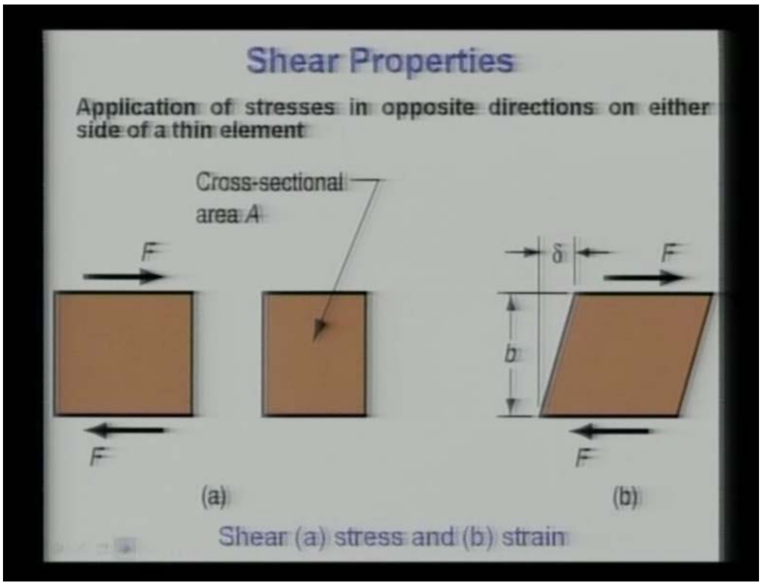

Now, shear properties this is the application of stresses in opposite directions on either side of a thin element, so essentially this shear properties each causes the angular distortion of the two opposite surfaces.

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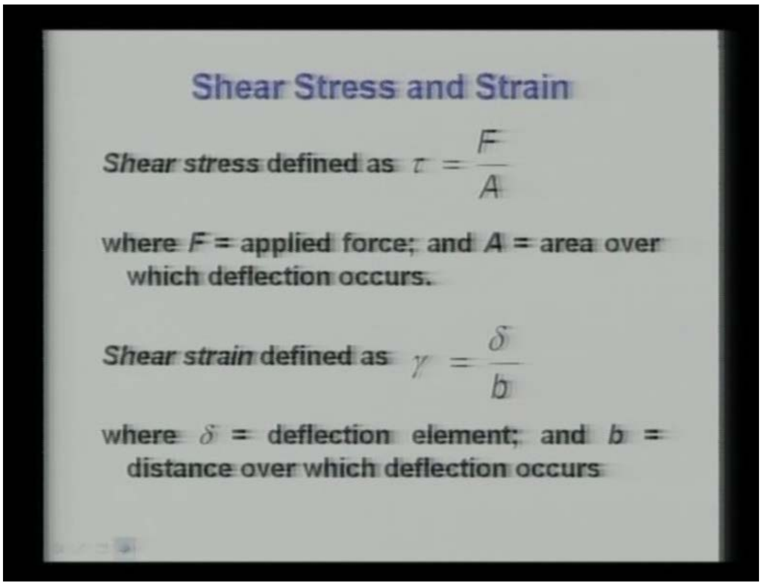

And here again the tau is defined as the equal amount of force, that you are applying to the cross sectional area and shear strain actually is this the distance between the two planes, that is b to the ratio of the delta and this b over delta is defined as the shear strain of a material.

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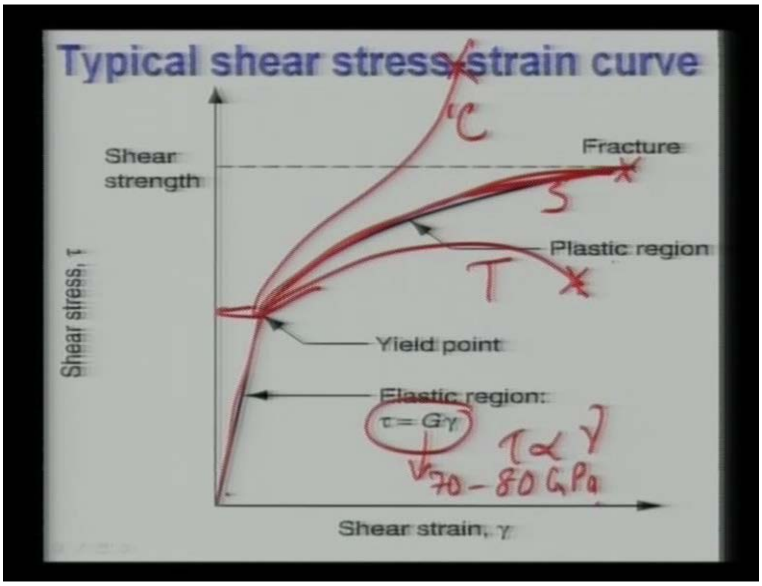

Now, how the shear stress shear strain curve looks like for a ductile metal, now like tension and compression your shear stress shear strain curve also will show initially linear part; that means, initial response of the shear stress or initial response of a material to a shear stress to the application of a shear stress will follow a linear part; that means, if you release it the material comes back to 0, then it is followed by non-linear fashion, then it goes to fracture of the material and this fracture of the material, that takes place reasonably at higher shear stress region and that is defined as the shear strain.

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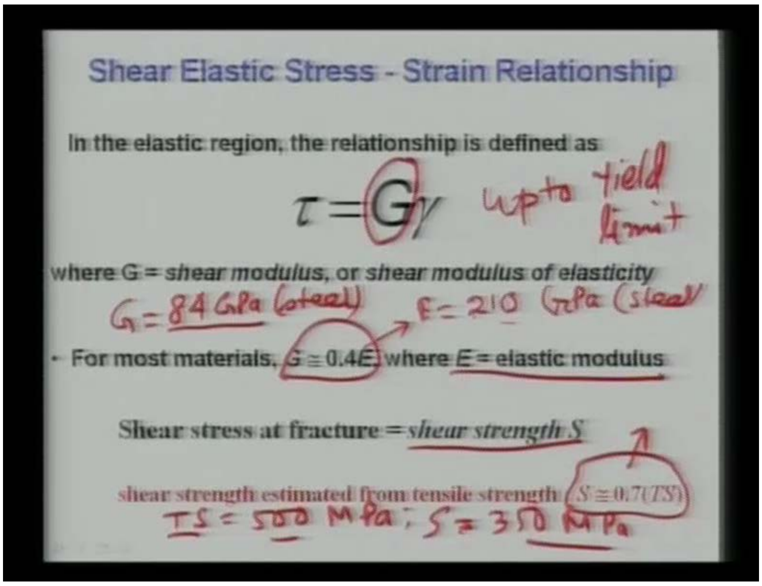

In the linear region tau is equal to G gamma is actually valid and tau is equal to G gamma means, tau is proportional to gamma, in other words shear stress is proportional to shear strain and constant of proportionality is known as the shear modulus G and this g is typically 70 to 80 gigapascal for most of the metals and again it is a shear yield point the either way you have seen for the tension test; now you on the same plot if I summarize that, how the tension compression and shear will be different or the response of a material to a tension force tensile force or compressive force or shear force will be different I will direct to summarize this, so that you can understand these three things in a same plot.

So, this is let say for tension, this one is for shear that is S and this one is compression that is C, what you see in the compressive strain typically is much is typically higher than tension or equal to tension, but in compression, that material undergoes more and more material has the capability to take more and more load in the shear stress again it goes to a non-linear manner, but in the tension case it goes through necking and this necking does not occur in case of shear and compression.

That is why tension force you have a completely different type of behavior compare to that of compression, as I said tau is equal to G gamma that is up to the shear limit.

So, that is up to the yield limit, this is up to the yield limit so, tau is equal to G gamma and G is the shear modulus and for most metals g is equal to .4 e, where e is the elastic modulus.

So, shear stress of the fracture is kind of shear is called shear strength and shear strength is roughly .7 T S, so this kind of relationship are valid for the wide range of materials like that, if you know the elastic modulus of a material for example, to give a an example elastic modulus of steel, that is 200 ten gigapascal. Now, this is elastic modulus of steel e value, so therefore, G value would be roughly around 84 gigapascal, so this 84 gigapascal is essentially calculated that G is equal to .4 E Now, tensile strength of a typical steel material, now if the tensile strength is around 500 megapascal, so these kind of values are important for you to understand that, what is the strain value of this materials. Now, if it is 500 Mpa, then the shear strength value would be roughly around 350 Mpa, that means, in case of the when we apply the shear stress to a typical stainless steel, then it can bear up to the 350 Mpa of the shear stress.

And tensile strength is around 500 Mpa and here the slope value when I draw the tensile stress tensor, the slope will be much steeper compare to that of the shear stress, now if you plot it here this is the tensile stress strength curve, so if this is the this is the tensile stress strength curve, then your shear stress strength curve would be little bit more flat and then it will be likely; because this is your shear, because this slope will be tensile slope will be much steeper compare to the shear stress and that is the reason that, they are sequentially that will be at the lower level, then compare to the tensile stress strength curve.

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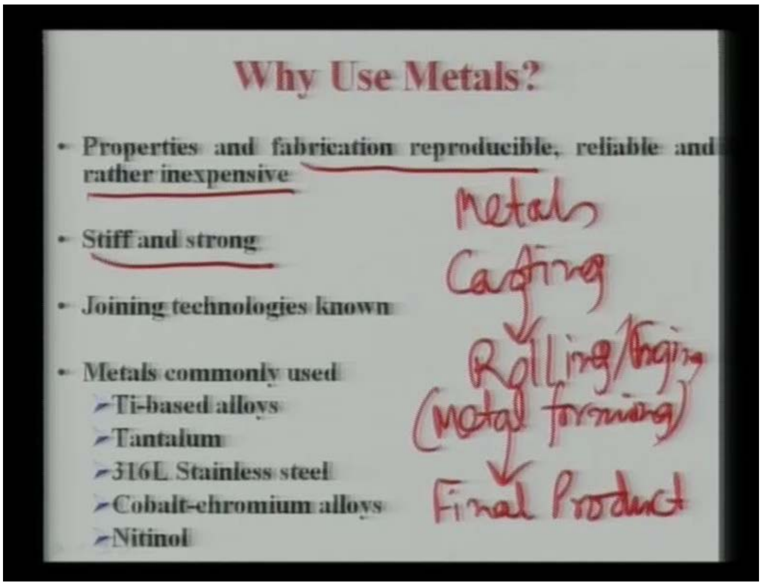

Now, coming back to the example of the some of the metals, now metals this is the processing of fabrication is reproducible, because typically metals the typical fabrication root would be casting and then rolling and then finishing product casting, rolling or forging or other other type of metal firming processes, what in general or generic name of this processes are the metal forming processes and then you go to the final product and then final product it can be either in the form of a plate, in the form of a sheet or in the form of a rod and depending on that, you can add of a sequence of processes which are particularly applicable; so this is production fabrication is reproducible and they are rather inexpensive.

Metals are stiff and strong as I said the typical it was tensile strength around 500 Mpa, now joining technologies are known, joining technologies means suppose you want to make a complicated part of a metallic bimetallic part, then you want to join the two parts for example, this is one part and this is another part, now typically this welding process is also quite standard or quite known and these welding processes or joining process can be easily adopted for a particular application.

Now, most metals which are most commonly used for this kind of biomedical application, they are like titanium based alloys, tantalum 316 L, stainless steel, cobalt chromium alloys, nitinol.

Now, if you recall yesterday's lecture I have told, that nitinol is a safe memory alloy cobalt chromium alloys they can be used as the knee joint or stainless steel this is these are used the mostly as the plates or screws, now titanium based alloys they can be used as the same of that artificial hip, that is the total hip replacement part, so these are like standard use of these different metallic materials.

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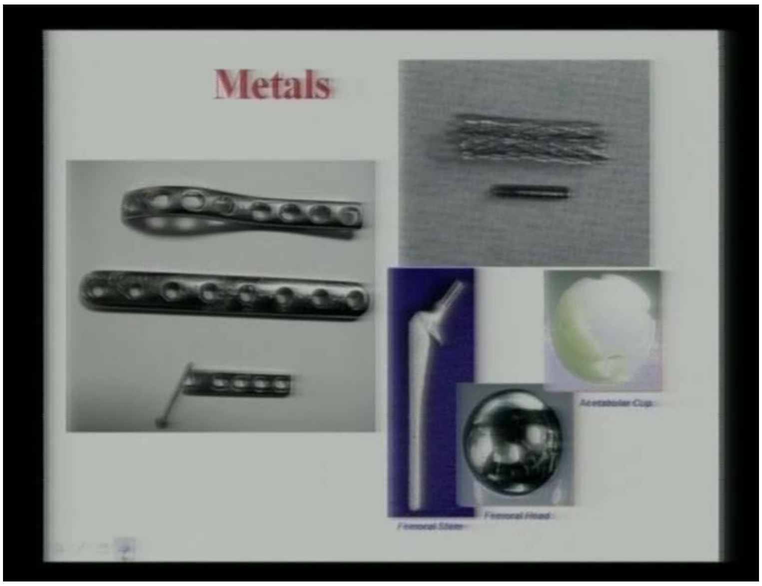

Now, these are like this slide particularly says you that, what are the different type of product that are possible when you use the metal now you can see because metals are essentially ductile and they are deformable you can make the holes of different sizes on this typical metallic part, this is a typical metallic plate and these typical metallic plate you have this kind of holes here and these holes you can make it by a standard technique and this plate with this holes in this metallic plates you can put it for a particular biomedical application.

Similarly, you can see here, this is like typical screws of the metals and stainless steel metals, that you can use you can use as a femoral head also the steel ball also can be used as the femoral head, but typically ceramic balls are preferred why because, ceramic balls has a longer durability and these are like acetabular cup this is the total femoral stem which is typically made up either stainless steel ss or titanium, if the patient can fear costly hip then, they can go for titanium because it was a better photocell resistance and better strength property, if the patient wants very cheap, then it can go for, if you can go for the stainless steel femoral strain.

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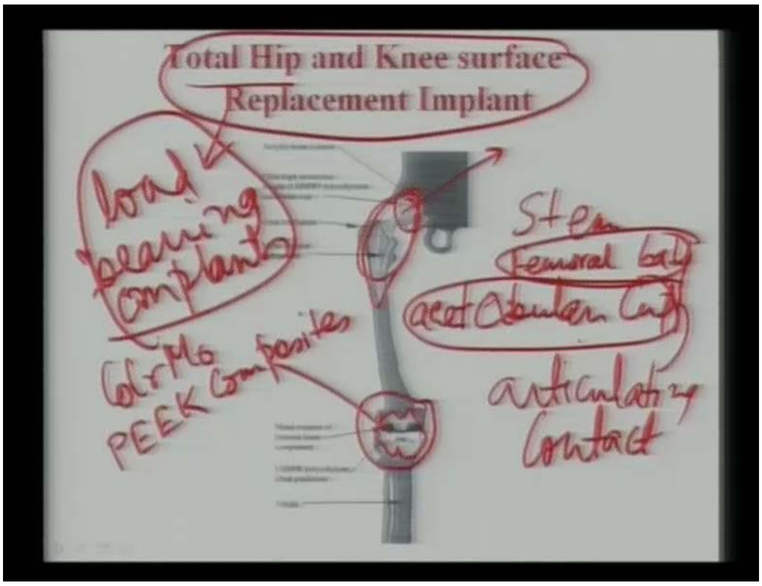

So, this particular slide shows the the different components of a total hip replacement and total knee replacement, so in case of total of hip you can see that, this there are three components here, one is the stem, the second one is the femoral ball hip and third one is the acetabular cup.

Now, these three components are mechanical integrated into these particular compact area here and this total stem is also surrounded by the natural tissues and bone; however, there is a intimate mechanical contact here, where this femoral ball is in direct contact with acetabular cup and these are like at the articulating contact.

Now, this articulating contact essentially indicates that, here that this femoral ball will experience is bound to experience the friction and where when well in contact with acetabular cup which is made up the polymeric material, this particular area is called knee joint and in this knee joint application what you can see, again it is load bearing kind of part and this load bearing part can be either made of the cobalt, chromium, molly alloy or it can be made of up some polymeric materials like polyether ether ketone like high load bearing materials and their composites.

So, essentially in both this total hip and total knee replacement these are essentially examples of the load bearing implant, here like in addition to biocompatibility mechanical properties are equally important in both the case of total hip and total knee replacement.

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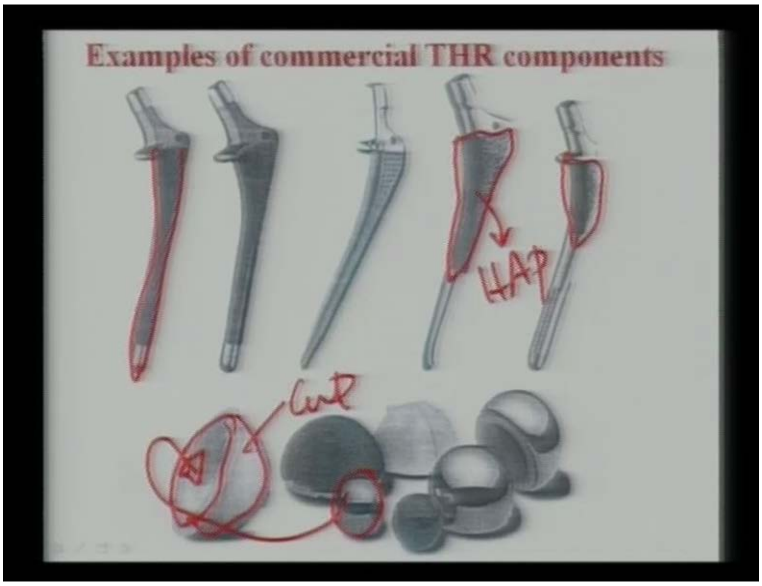

These are the examples of the commercial total hip replacement components, what you can see that this stem part, now this stem part can be coated or this can be uncoated also; now this is the example of the hydroxyapatite coated titanium femoral stem or this can be coated on that stainless steel substance also; now why hydroxyapatite coating is required on this titanium stem, because the hydroxyapatite as I have mentioned in the first lecture, it is essentially highly biocompatible and bioactive materials, so when you put this hydroxyapatite coating here, then it will enhance the oscine integration or put biocompatibility in vitro in vivo biocompatibility of this material.

Now, these are the examples of the acetabular cup, which is typically used in this total hip replacement and this cup actually has, this cup can (()) this kind of femoral ball.

So, this can be directly treated inside this acetabular cup during this total hip replacement operation.

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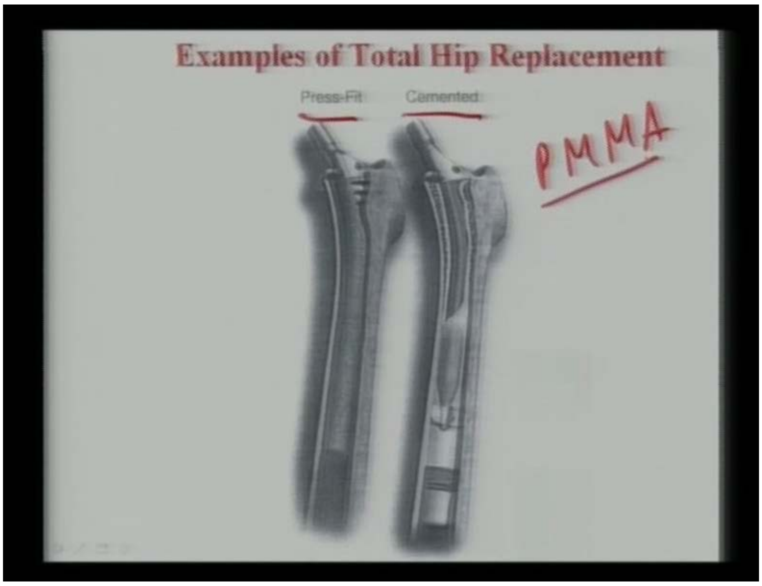

So, now, this cup can be made up metallic, this cup can be made up the polymeric parts also, now this is like two different types of total hip replacement materials, one is the press fit and one is the cemented; cemented means this cementing material here it is used is there polymethyl methacrylate that is PMMA, that is widely used as a bone cement materials.

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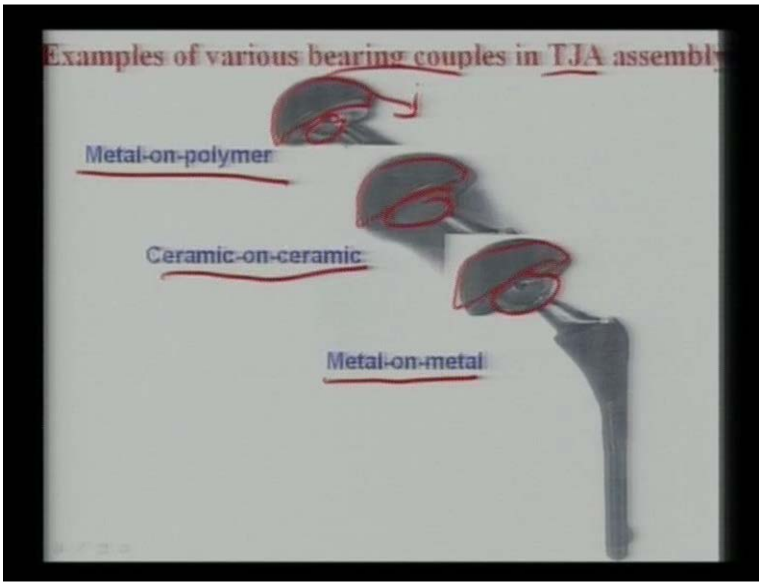

Now, there are three combinations of the bearing couples in the total joint orthoplasty. So, TJO stands for Total Joint Orthoplasty, THR stands for Total Hip Replacement, total hip joint replacement, now in this total joint orthoplasty what you can see here, this is the metallic ball and this is the polymeric cup.

Now, you you can you can create this ceramic cup also and you can get this ceramic ball also and and you can get this metallic ball as well as this is can be metallic cup, so you can have this bearing couple metal, on metal it can have bearing couple metal one ceramic on ceramic, you can have the bearing couple which is composed of metal on polymer. So, therefore, this is not something sacrosanct, that you need to use the polymeric material all the time for this acetabular cup, one can use this metal, one can use this ceramic also as an acetabular cup materials.

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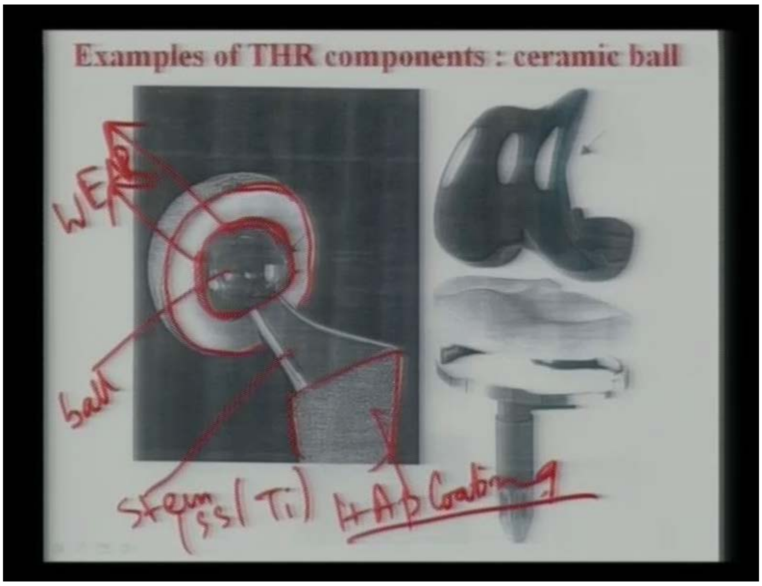

This is exactly what I was trying to explain to you for last few minutes that, this is the end of the femoral ball and this is you acetabular cup here and this acetabular cup here, actually housing this femoral ball, so this is your ball femoral and this is your acetabular cup.

Now, these surface two surfaces they are compete in the reciprocating motion and because of this reciprocating motion, this wear resistance is important at the surface, so both the friction and wear resistance are important at the surface and this is your hydroxyapatite coating on the femoral stem and this hap coating as I have said is done from biological perspective and this is your uncoated femoral stem which can be either made of stainless steel or titanium material.

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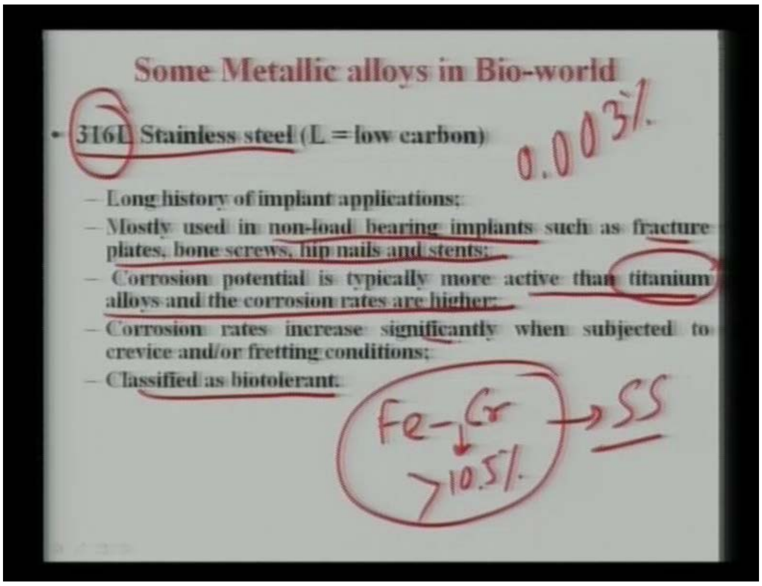

Now, some of the metallic alloys which are used in biomedical applications for example, 316 L stainless steel and now stainless steel means it is essentially an alloy of iron and chromium and here the chromium content is typically more than 10.5 percent. So, any alloy which is iron chromium and this chromium content is more than 10.5 percent or more, then you can call it as a stainless steel, that is the standard definition of stainless steel.

Now, depending on what is the different alloying elements which are further added to this stainless steel you can (( )) stainless steel, which is essentially for 316 stands for you can have a fairlead stainless steel or you can have a martensitic stainless steel, but the fundamental definition of stainless steel means, this is an alloy of iron and 10.5 percent minimum amount of chromium, that should be there is called 10.5 percent; stainless stainless means like if you want to scratch on this material, you would not be able to make a scratch, because this material are extremely resistant to corrosion and wear on this particular stainless steel composition when you use the standard designation L, L means low carbon content and this low carbon content may be as low as .003 percent of carbon in this stainless steel.

Now, this stainless steel alloys these are mostly used in non-load bearing implant such as fracture plates, bone screws, hip nails and stents and corrosion potential is typically more active than titanium. Therefore, that many of the high durability or longer resistant to corrosion titanium alloys should be used and their corrosion rates are higher and this is consider as a biotolerant and this corrosion rates increase subsequently when subjected to crevice or fretting conditions.

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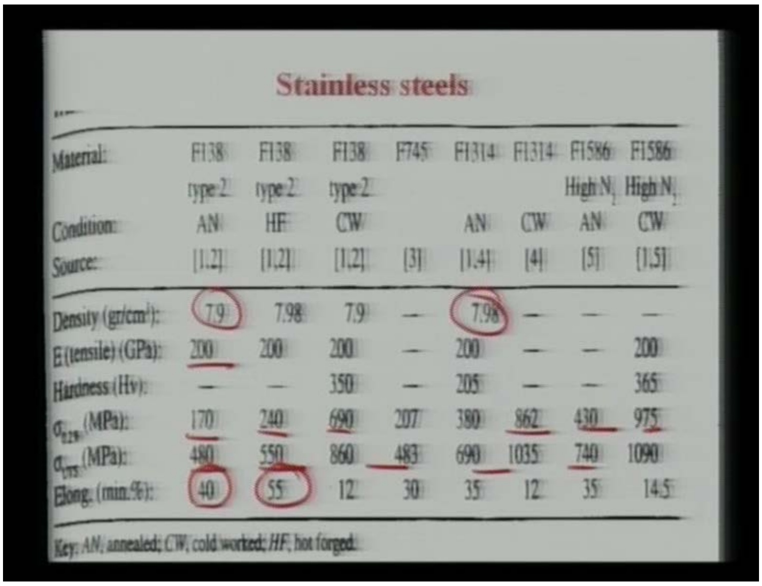

Stainless steels

Material:	F138 type 2	F138 type 2	F138 type 2	F745	F1314	F1314	F1586 High N_2	F1586 High N_2
Condition:	AN	HF	CW		AN	CW	AN	CW
Source:	[1,2]	[1,2]	[1,2]	[3]	[1,4]	[4]	[5]	[1,5]
Density (gr/cm^3):	7.9	7.98	7.9	—	7.98	—	—	—
E(tensile) (GPa):	200	200	200	—	200	—	—	200
Hardness (Hv):	—	—	350	—	205	—	—	365
$\sigma_{0.2\%}$ (MPa):	170	240	690	207	380	862	430	975
σ_{UTS} (MPa):	480	550	860	483	690	1035	740	1090
Elong. (min.%):	40	55	12	30	35	12	35	14.5

Key: *AN*, annealed; *CW*, cold worked; *HF*, hot forged.

These are some of the commercial (( )) stainless steel, what you can see here that it has a very higher density 7.8 as I had mentioned in the yesterday's lecture that a typical ceramic which is a density of around 3.9 naught 4 which is almost like half of that, of the mostly steel based alloy, it has elastic model as I said it around somewhere around 200 to 210 gigapascal it has a yield strain quite low like 240 and apart it can go up to thousand megapascal, elastic UPS is roughly around 500 megapascal to as high as 1000 megapascal, it has elongation to fracture it is 40 to 55 percent so; that means, large elongation to fracture is possible in this materials.

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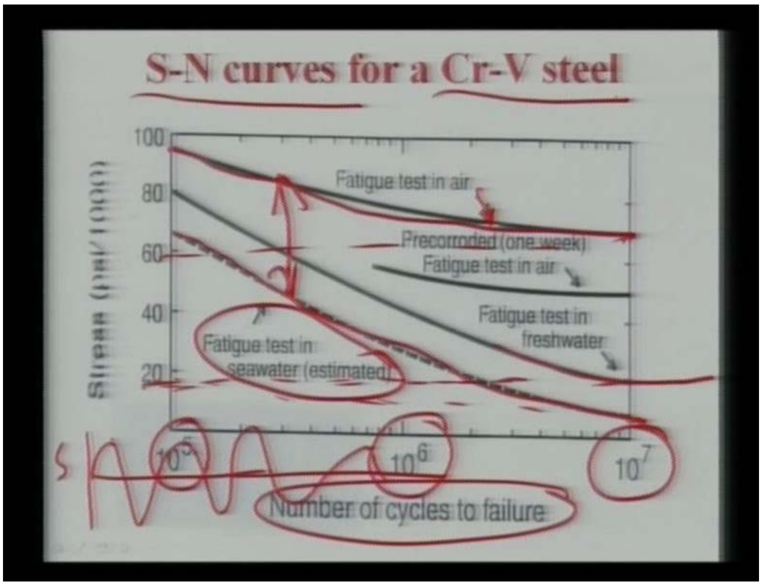

This is the typical S-N curve from chromium-vanadium containing stainless steel, what you see here, that these S-N curve essentially indicate that what is the typical life of this stainless steel materials when it is subjected to stress cycle; stress cycle means now, if it is a tension now, tension it can be sinusoidal stress cycle like stress will increase then decrease, so this is the stress here.

So, how many cycles, number of cycles to failure and these number of cycles can be 10 to the power of 5, 10 to the power 6, 10 to the power 7, larger the number of cycles more data repeats preferred in the real life application also, that what is the typical fatigues strain typically, the fatigue strain denoted like where this S-N curve becomes more and more flat, now this threshold stage value is called the fatigue curve is defined as the fatigue strain.

Now, what is important from note from this slide is that, when you do this fatigue test in air, now this fatigue curve S-N curve is relatively at much much higher level or higher region compare to when you do this test same fatigue test from the same material in sea water; now sea water means means it is a largely Nacl containing material solution and this sodium chloride solution here, essentially mimics the typical in which environment or typical body environment and therefore, what you can what you can really predict from this that you cannot really use the fatigue test, that are of any steel materials which you have obtained in air.

But you have to rely on the fatigue tests, that have which have obtained in the sea water for example, so that, you can conservatively estimate the typical fatigue life of that steel in real in which (( )) condition.

Because, you can see there is a large decrease in the fatigue strength here, when you compare the fatigue that are in air with, that of a fatigue that are in the sea water and than other things is that also this static strength here is around somewhat 60 megapascal in case of the fatigue test in sea water if it is less than 20 Mpa, so it is three times decrease in the fatigue strain of this chromium vanadium containing steel.

So, this is just an illustration this kind of behavior is also replaced in other in other materials, so general nature or general message from this slide is that, typically fatigue strain behavior of fatigue behavior in sea water is degraded when you compare the same behavior in simple air or ambient condition.

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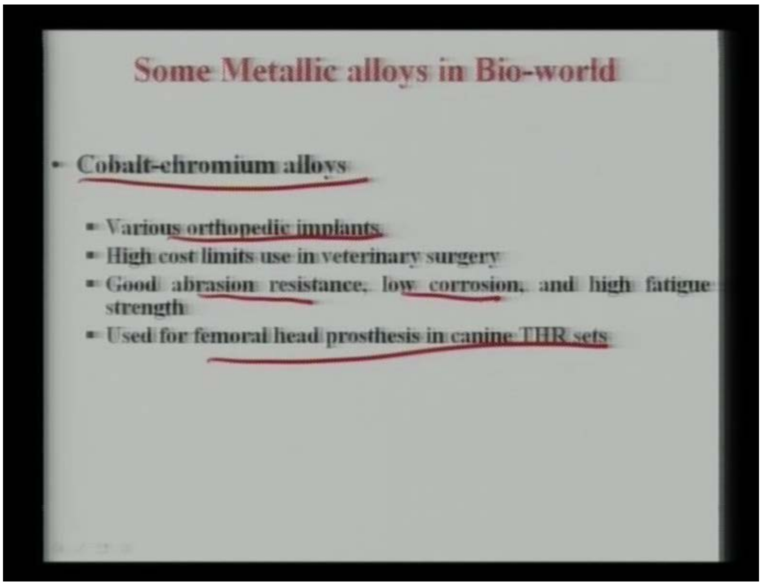

Now what is the other alloys which are used in the biomaterials application like cobalt chromium alloy, now this cobalt chromium alloy they can be used for various orthopedic implant applications as I said for the knee joints for example, this is used for (( )) head prosthesis in canine THR sets and it has good abrasion resistance and low corrosion properties of these material.

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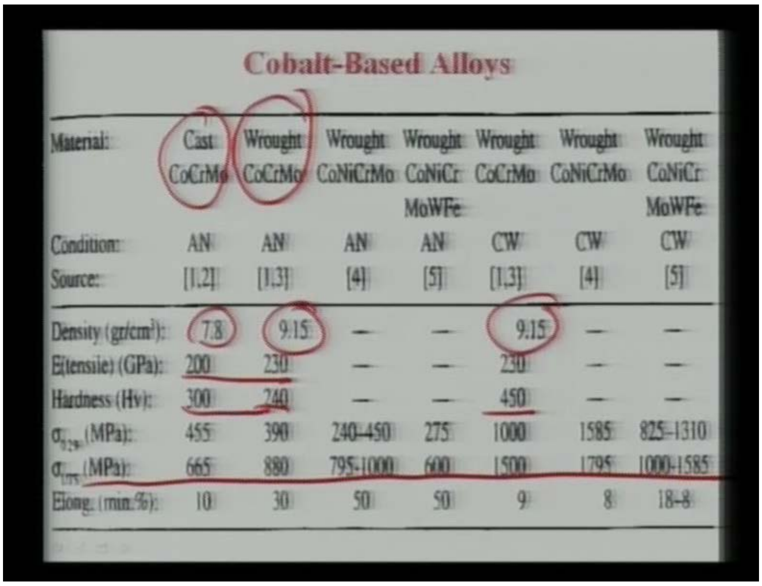
Cobalt-Based Alloys

Material:	Cast CoCrMo	Wrought CoCrMo	Wrought CoNiCrMo	Wrought CoNiCr MoWFe	Wrought CoCrMo	Wrought CoNiCrMo	Wrought CoNiCr MoWFe
Condition:	AN	AN	AN	AN	CW	CW	CW
Source:	[1,2]	[1,3]	[4]	[5]	[1,3]	[4]	[5]
Density (gr/cm^3):	7.8	9.15	—	—	9.15	—	—
E(tensile) (GPa):	200	230	—	—	230	—	—
Hardness (Hv):	300	240	—	—	450	—	—
$\sigma_{0.2\%}$ (MPa):	455	390	240–450	275	1000	1585	825–1310
σ_{UTS} (MPa):	665	880	795-1000	600	1500	1795	1000-1585
Elong. (min.%):	10	30	50	50	9	8	18–8

Now, these are like some other commercially available, cobalt chromium alloy as you can see it can be a kit is available in a cast form or it can be available in the wrought from, in all this cases it has also very large density like 7.8, 9.2 their elastic modular similar like that of steel, they have AUTS of 656 56 (( )) 1000 or 1500 megapascal it has also hardness in the weaker scale it is, it can go up to 450 weaker hardness numbers.

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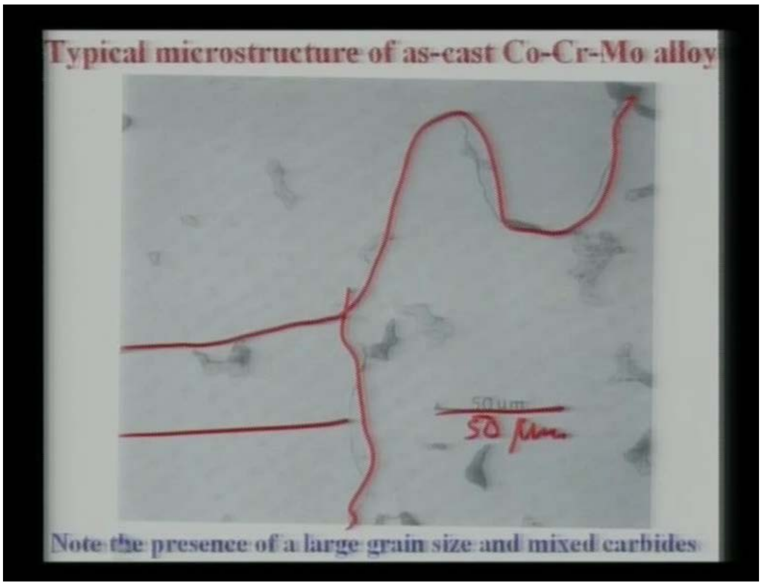

This is a typical microstructure of a cobalt chrome as cast cobalt chrome molly alloy as you can see this is a part of the grain boundary and here grains are effectively very large.

So, this s is your 50 micro microns scale right and so therefore, this is a part of the grain and so, the grains has here can be as I has 200 to 300 micrometers, which is quite large grain.

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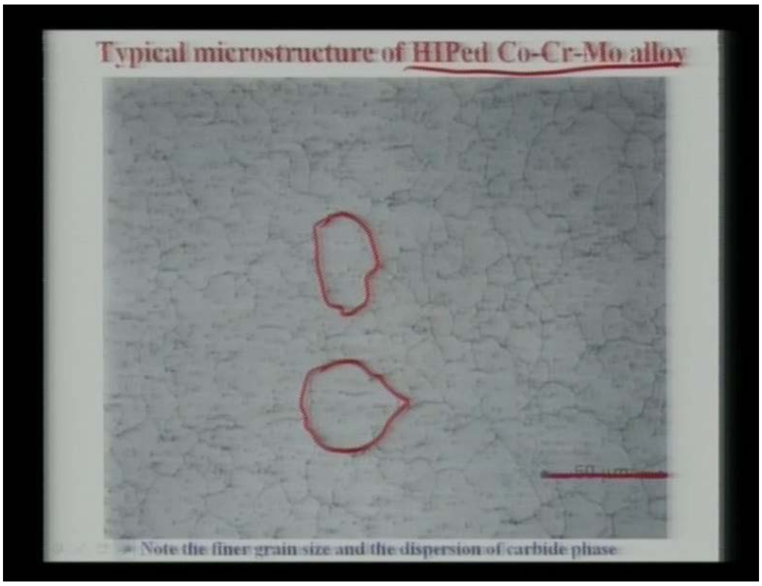

This is what as statically press cobalt chrome molly alloy, what you can see here this grain size is all though here very large and it is a very irregular kind of grain boundary all the grains are equivalent in nature and from this 50 micron you can see when you do this hip or the hot isotopic pressed alloy, then you can essentially reduce the grain size because of the large patient that you will do, that will apply during the compaction process.

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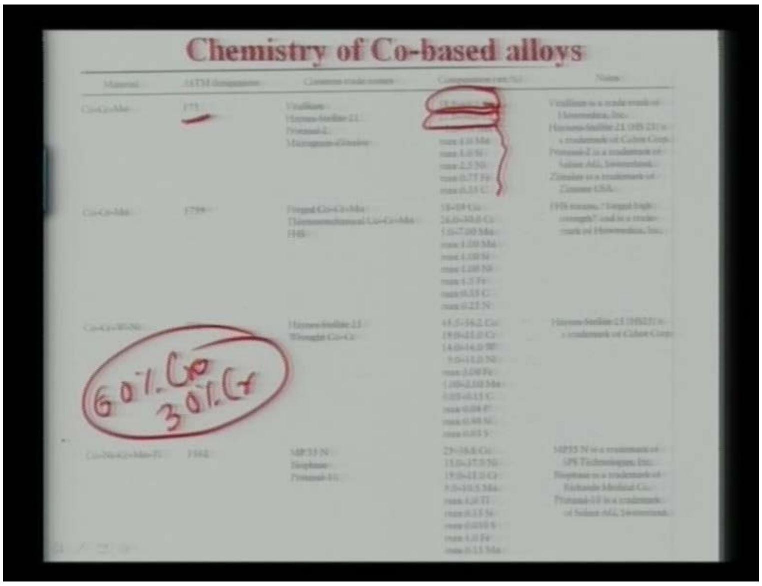

So, this slide actually tells you some of the compositions of the cobalt chrome molly alloy and here it is like K f 75 breed which is widely used in the biomedical applications here it has a 58 to 69.5 percent cobalt and then up to 30 percent you have chromium and trace that all other alloying element.

So, mostly your cobalt content is around roughly around 60 percent cobalt and you are, so this is your cobalt and around 30 percent is chromium, rest is the molley and other elements, so this is like a standard cobalt cobalt chrome molly alloy commercial composition.

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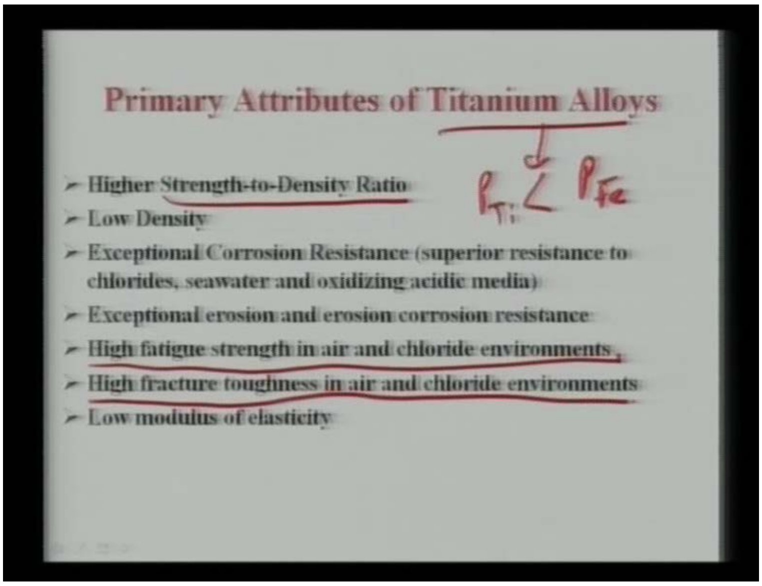

Now, coming to the titanium alloy, now this titanium alloys they have a very good strength to density ratio because, the titanium alloy the density rho titanium is much less than rho ferro or steel. So, therefore, when you divide the strain by density you get the higher specific strength values of the titanium it has a good exceptional corrosion resistance because, the titanium metal is the corrosion resistance is much better than at that of the steel materials, it has good fatigue strength much better than air, much better than that of the steel materials and it has also high fracture toughness in air and chloride environment.

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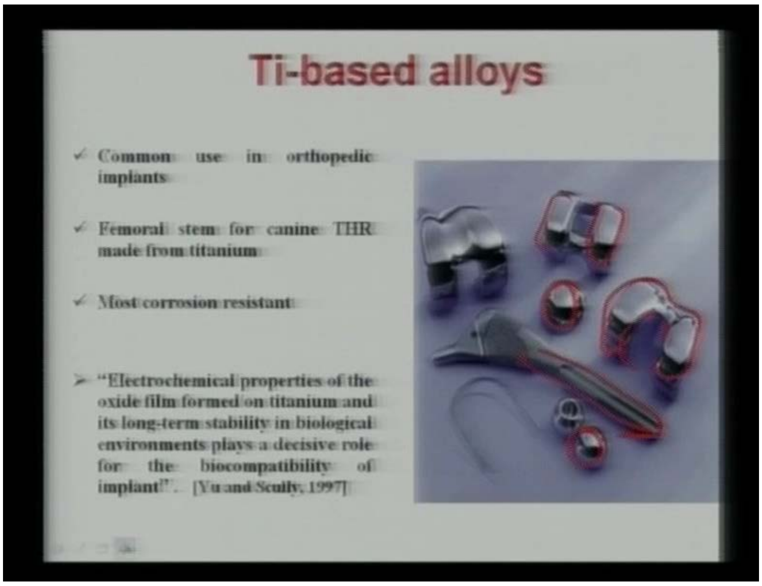

Some of the titanium based alloys are shown, which are used in the orthopedic application, now as you can see that these titanium alloys they are also available in different size as well as different shape, you can get titanium balls, you can get titanium femoral stem here, so all these applications are possible because of the combination of properties, that they exhibit as an I just mentioned; now titanium one of the very well known great which are widely used, that is titanium 6, aluminum 4, vanadium.

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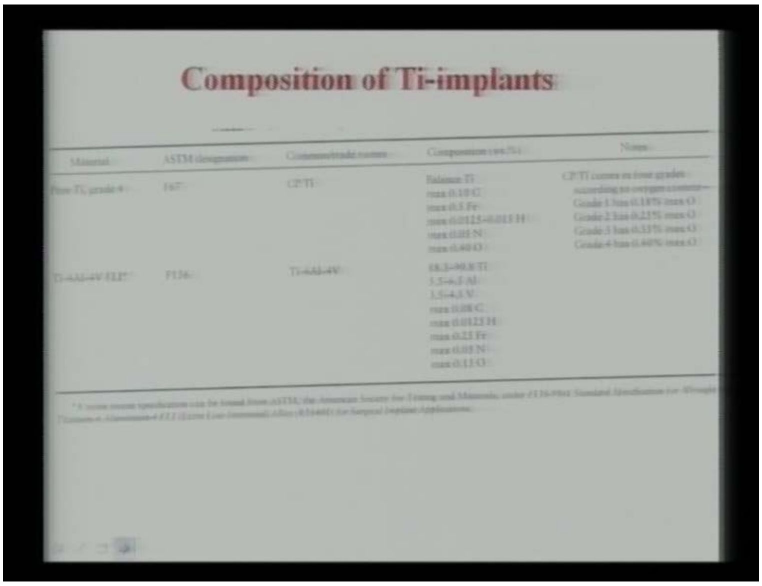

So, this T i 6, L 4 V is widely used as the composition suggest, that it has a 6 percent roughly, 6 percent aluminum and roughly 4 percent vanadium and rest is most of the other allowing elements like carbon and so on, but very small amount and this titanium and then other one is the commercially pure titanium, so here the all the allowing elements in the combination is roughly around less than 1 percent, so this is less than one percent and it has a 99 percent purely titanium.

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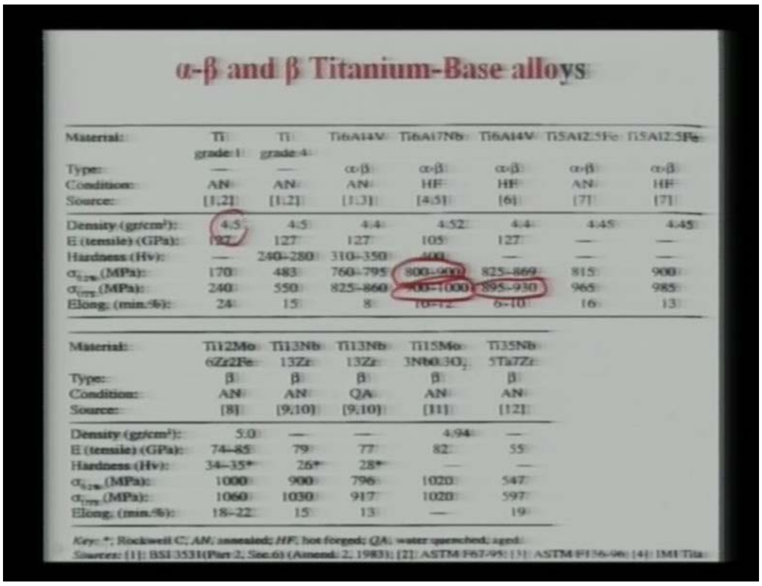

Material:	Ti grade 1	Ti grade 4	Ti6Al4V	Ti6Al7Nb	Ti6Al4V	Ti5Al2.5Fe	Ti5Al2.5Fe
Type:	—	—	α-β	α-β	α-β	α-β	α-β
Condition:	AN	AN	AN	HF	HF	AN	HF
Source:	[1;2]	[1;2]	[1;3]	[4;5]	[6]	[7]	[7]
Density (gr/cm³):	4.5	4.5	4.4	4.52	4.4	4.45	4.45
E (tensile) (GPa):	[illegible]	127	127	105	127	—	—
Hardness (Hv):	—	240–280	310–350	400	—	—	—
$\sigma_{0.2\%}$ (MPa):	170	483	760–795	800–900	825–869	815	900
σ_{UTS} (MPa):	240	550	825–860	900–1000	895–930	965	985
Elong. (min.%):	24	15	8	10–12	6–10	16	13

Material:	Ti12Mo6Zr2Fe	Ti13Nb13Zr	Ti13Nb13Zr	Ti15Mo3Nb0.3O$_2$	Ti35Nb5Ta7Zr
Type:	β	β	β	β	β
Condition:	AN	AN	QA	AN	AN
Source:	[8]	[9;10]	[9;10]	[11]	[12]
Density (gr/cm³):	5.0	—	—	4.94	—
E (tensile) (GPa):	74–85	79	77	82	55
Hardness (Hv):	34–35*	26*	28*	—	—
$\sigma_{0.2\%}$ (MPa):	1000	900	796	1020	547
σ_{UTS} (MPa):	1060	1030	917	1020	597
Elong. (min.%):	18–22	15	13	—	19

So, which is called commercially pure titanium, now this titanium alloys are also available in different from like alpha beta titanium alloys or beta titanium alloys and here as this particular slide shows the different kind of properties, that you are available at different variation of properties; now some of the properties I must mention here like it as it can have been instant of 900 megapascal and also it has a ultimate tensile strength which is always close to 1000 megapascal or 1 gigapascal.

Now, this 1 gigapascal is roughly around double than that, of the ultimate tensile strength of steel based material, that one can achieve and therefore, titanium has much higher strength property than that of steel this particular fact I must emphasis here. Another fact that I should emphasis the titanium also has a has a very low density and their density values is around 4.5 gram per CC which is smart less than that of the steel, which is around to 7.8 gram per CC other factors is that elastic modular.

So, one is the density of the titanium, one is the good UTS values and third one is the elastic modular, now elastic modulus of steel as you have seen earlier it is somewhere around 210 gigapascal. But elastic modulus of titanium is roughly around 100 or 105 or 110 gigapascal. So, which is almost half of that, of the titanium, half of that of the steel based materials and your cortical bone this has the elastic modulus of upper bound of the elastic also cortical bone is around 80 gigapascal.

So, titanium elastic modulus is close to that of the cortical bone and therefore, from mechanical point of view also titanium is highly preferred, because it somehow closely matches with the upper boundary elastic modulus of the cortical bone.

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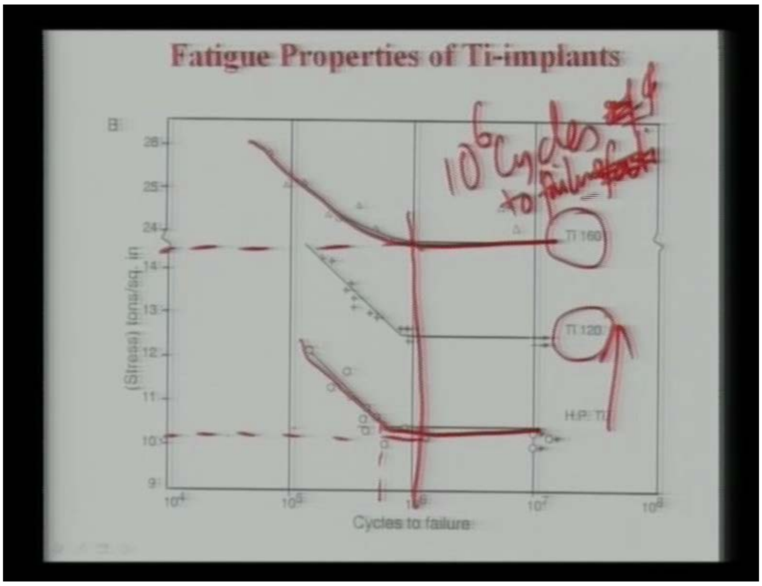

Now, this is a kind of fatigue properties of the titanium implants for I will emphasis here like when you plot the stress for the cycles to failure here, now if you high purity titanium which has a extremely low fatigue value; now these are like different alloys of titanium with aluminum or with aluminum and penatanium and so on, what you notice here that, with increase in alloying element your fatigue strain is also increases.

Now, here this is for tons per squaring, so it is around more than 14 tons per square inch whereas, in case of the (()) titanium it is roughly around 10 tons per squaring, the cycles to failure it remain same that is around 10 to the power 6, but in case of (( )) it is less than 10 to the power 6, so it is 10 to the power 6 cycles to failure, that is the typical fatigue life of titanium.

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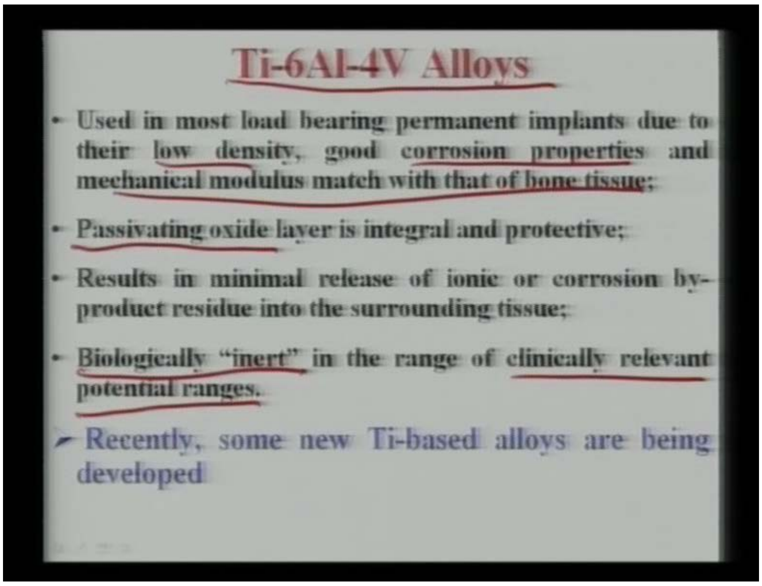

So, 10 to the power 6 cycles to failure, that is the typical fatigue life of titanium based materials; now titanium 6 aluminum four vanadium there is one slide one that, because it is mostly commercially well used for biomedical applications and it is used because, it has a very low density good corrosion properties and good mechanical properties which match closely, that is the bone tissue and this corrosion properties is basically it is the passivating oxide layer, that forms on the titanium 6 aluminum 4 vanadium it is biologically inert like it is not bi-active in the range of clinically relevant potential ranges. So, inside the human body you have the electro chemical potential and in this potential region it is titanium 6 aluminum 4 vanadium is biologically inert.

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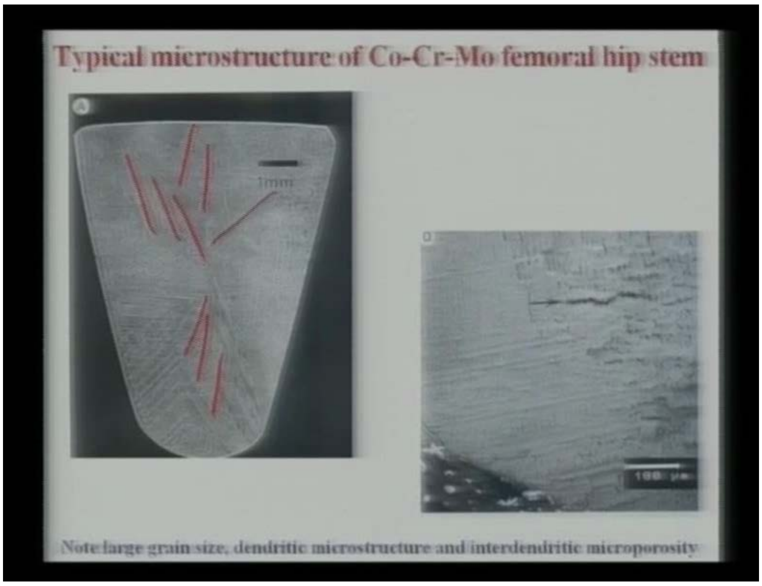

These are like typical microstructure of cobalt chrome moly femoral stem it has a typical cast structure like columnar structure, so this all this columnar cranes are oriented at different orientations and this form during the casting solidification process.

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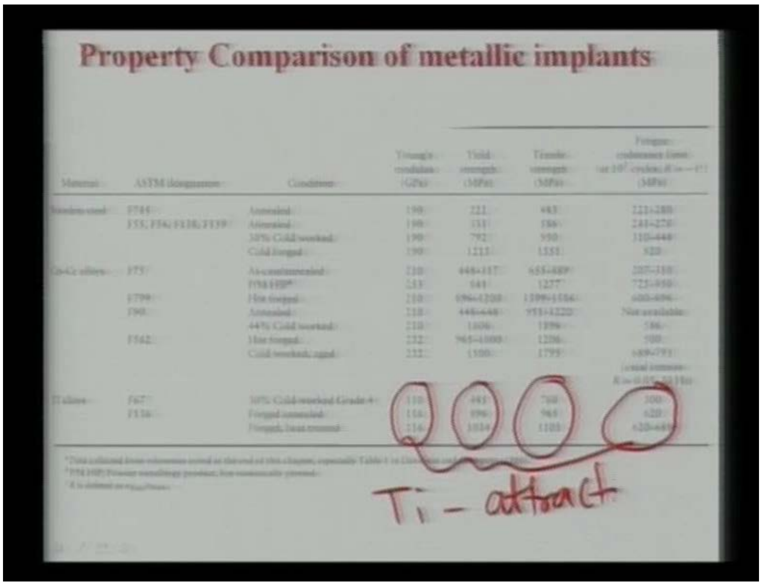

This is the property comparison of some metallic implants like you start with the some commercial trades of some stainless steel with cobalt chrome alloys as well as titanium alloys.

What you can see the titanium alloys are far their elastic modulus is much much below than that of the stainless steel cobalt chrome moly alloys it has a good elastic yield strength as well as good tensile strength and also it has a good fatigue limy. Now, all this combination of properties that makes titanium, most attractive material from biomedical point of view, this is the typical microstructure of the cold worked commercial pure titanium, these are somewhat (( )) type of microstructure also you have the (( )).

Now, this (( )) stones if this is 40 micron this is roughly 20 to 40 micron is the grain size of this commercially pure titanium, now this is the typically titanium 6 aluminum 4 vanadium alpha beta alloys, that is the microstructure.

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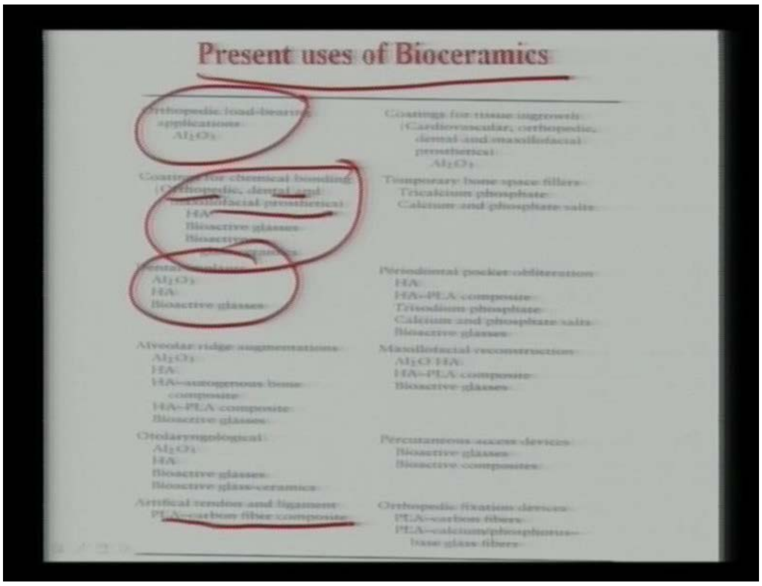

Now, this particular slide actually if summarizes the potential uses of bioceramic, now bioceramics must be that orthopedic applications is the alumina is used for coatings for chemical bonding orthopedic dental application maxilla, maxillofacial prosthetics that is the hydroxyapatite bioactive glasses (( )) mostly used and some other dental application alumina hydroxyapatite bioactive glasses, may you have this artificial tendon and ligament that is the PLA carbon composite.

So, PLA it is poly lactic acid that is an example, of a one polymer and carbon fiber campsites these are used in the artificial tendon or ligament, so the specific properties of the ceramics and polymers like you know what is the strain properties, how their mechanical properties they they are different from that of the metals and from that of the metals that I will discuss more when I will when I will teach you the bioceramics or bioactive ceramics as well as the different biopolymers.

So, I think I will finish my lecture here.