Cryogenic Engineering
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Lecture No. #05
Materials Properties at Low Temperature

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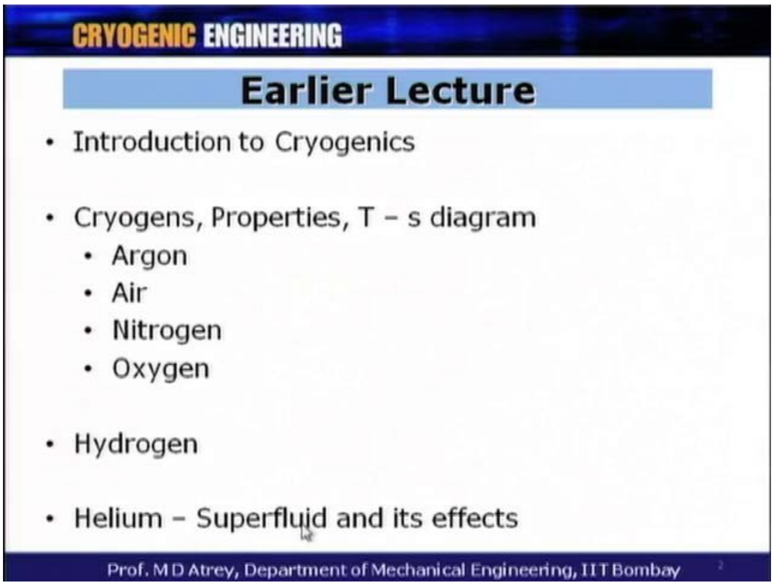

So, welcome to the fifth lecture on cryogenic engineering under is NPTEL program. Just taking a view of what we have done in the earlier lectures, we had introduction to cryogenics as topic one. And, in the topic two, what we had was the information regarding all the cryogens, the properties, temperature and (( )) diagrams. And we talked about various cryogens which are argon, air, nitrogen, oxygen, and then we went little bit in depth regarding hydrogen, and we talked about Ortho and Para hydrogen and its conversion. And also, we talked about helium, we talked about helium isotopes, which is helium 3 and helium 4. Also, we talk about normal helium 1, which is helium at 4.2 K helium liquid, and we talked about helium as super fluid which is helium 2.

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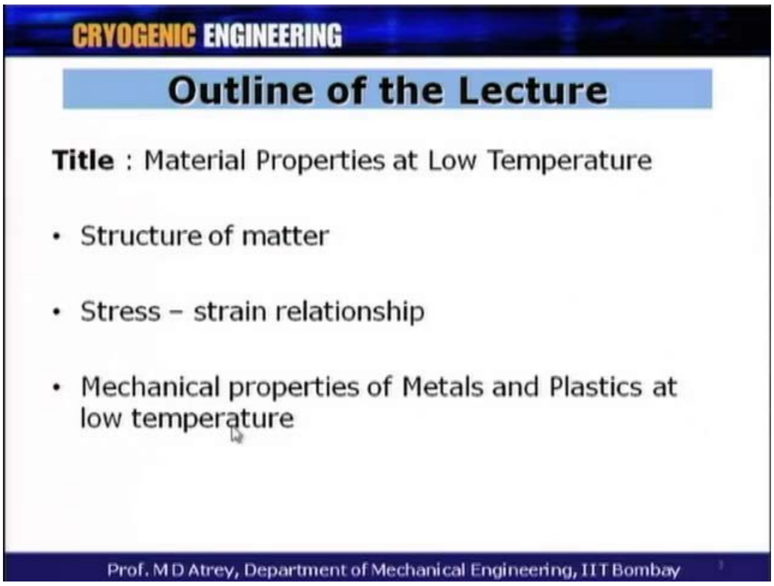

In this lecture, we will talk about material properties at low temperature. Ultimately, all this cryogens are kept in some cryo containers which are made of some material, metal and sometimes non metals. And therefore, it is very important to understand, how this materials behave at low temperature.

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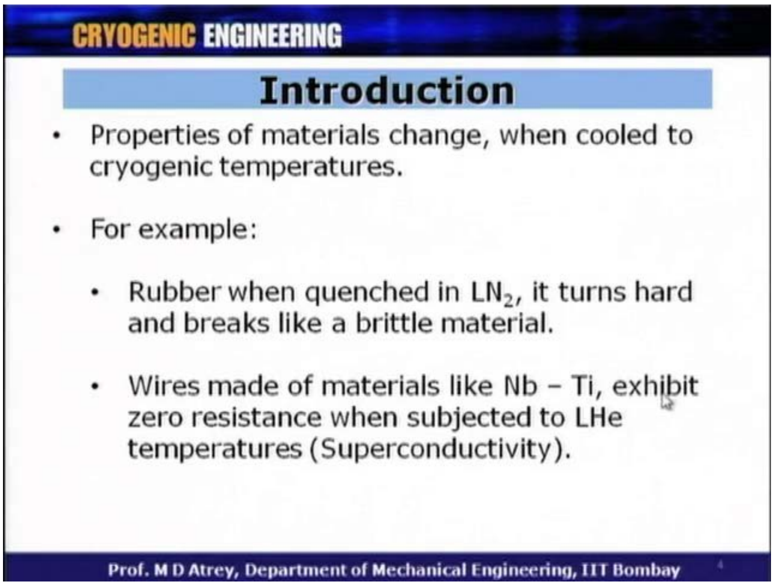

Wherein, we will study the structure of matter. Also, we will study stress-strain relationship for this material. And in this particular lecture; we will talk about mechanical properties of metals and plastics at low temperature. Why are we studying all these things? We want to study these, because the properties of material change when cooled to cryogenic temperatures and then sometimes these changes are drastic. For example, we have seen a video earlier and we will see the experiment again.

We can see from this experiment that rubber when it got quenched in to liquid nitrogen, it turns hard and it broke like a brittle material, which we just saw. We can also see sometimes, you know another experiment which we have not done yet. We can see that the wires made of material like niobium, titanium it exhibits zero resistance when subjected to liquid helium temperature. That means, this wire becomes superconducting wire, it shows R is equal to 0, I squared R is equal to 0; that is no joule heating.

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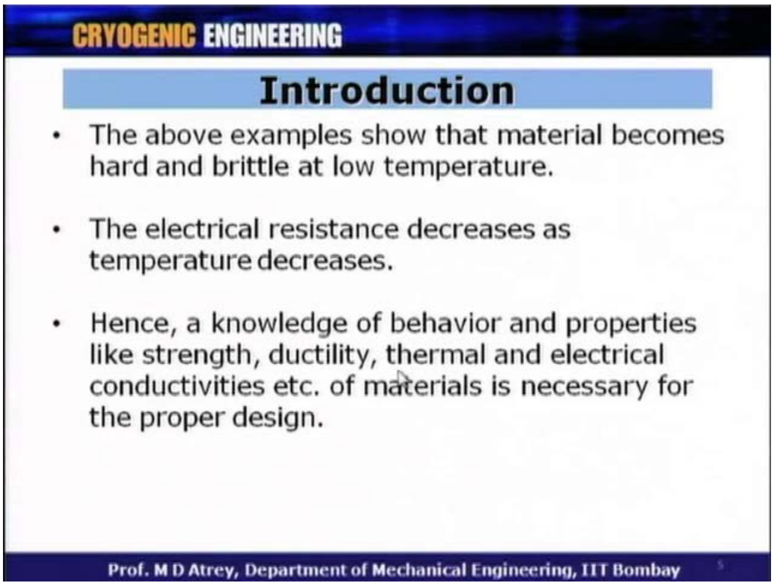

These are very important changes that happen in these materials and these examples therefore, show that the material becomes hard and brittle at low temperature. At the same time, the electrical resistance decreases as temperature decreases for certain materials. These two examples show that, material property do change drastically. In addition to these two property, which we have just shown to you as an example, we got several other properties like strength, ductility of material, thermal and electrical conductivity, specific it capacity, thermal expansion, all this property change at low temperature.

Therefore, the knowledge of this material property changes, at low temperature is very important for proper design of a material, which is going too subjected to low temperature. And this is what we plan to do in this particular lecture.

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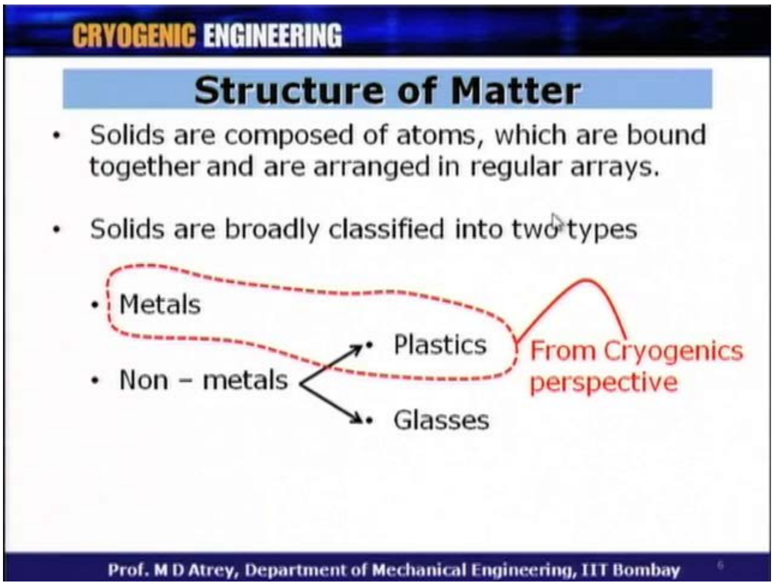

Before we study the property changes at low temperature, it is important to understand the structure of matter. Solids are composed of atoms which are bound together and arrange in regular arrays, we know this. Solids are broadly classified into two types; Metals and Non-metals. And in cryogenics we use both metals, as well as non metals. The non-metals are further classified into plastics and Glasses. Any cryo container for example, or any cryogenic equipment, we can have metals, we can have plastics and we can have glasses also.

While glasses make a very special case, most of the places, metals are used. And plastics are also used sometimes, to support these metals. And therefore, I am keeping this lecture limited to discussion regarding metals and plastics. And we will study the property variations of this material at a low temperature. So, from cryogenic perspective I will discuss metals and plastics only.

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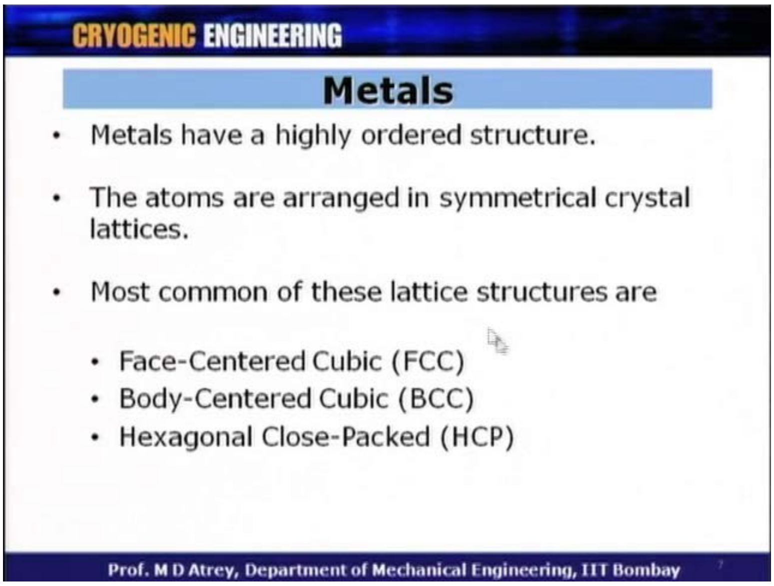

As you known, now we will come to metals. We know that metals have a highly ordered structure. The atoms are arranged in symmetrical crystal lattices. And the most common of this lattice structures are face centered cubic that is FCC material, body centered cubic, that is BCC material and hexagonal close packed material; that is HCP material. I think we all studied all these things in the material science. In the fundamentals of material science maybe in the first year or second year of engineering, we will just revise those fundamentals and find out what exactly FCC, BCC or HCP mean?

The face centered cubic structure has one atom at each of the eight corners and an atom at the center of each of the six faces. Here you can see a FCC structure, where you have got 4 plus 4; eight atoms. And, atom at the center of each of the faces and there are 6 faces. So, 8 plus 6 next, 14 atoms for FCC structure.

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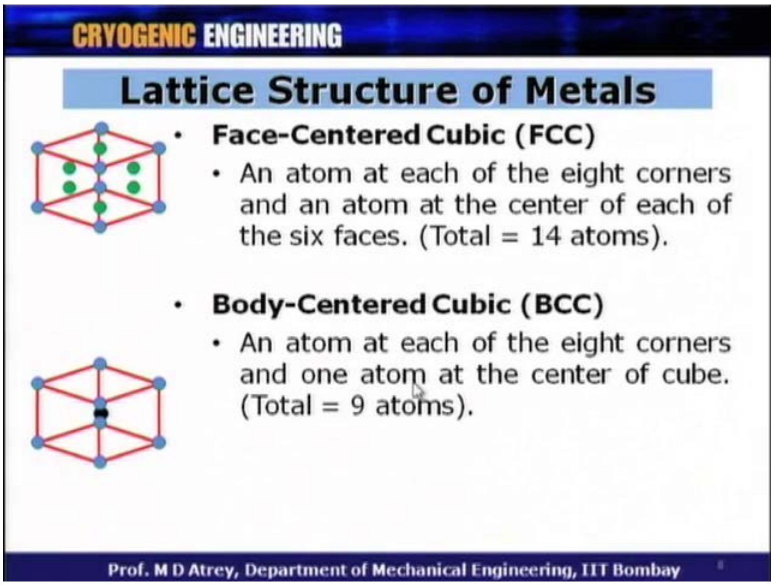

The BCC structure has an atom at each of the 8 corners and one atom at the center of the cube. That means there are eight corners, plus one at the center which makes it 9 atoms in total for BCC material.

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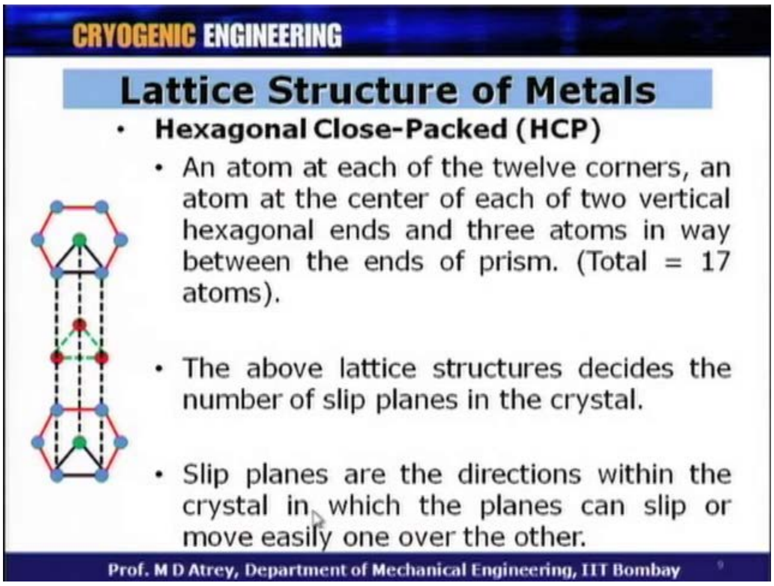

As, for as HCP material concern which is hexagonal close packed, we have got hexagonal site now. We have got two hexagons; one at a top and one at the bottom and there is the atom at each of this corner and this makes 12 corners. So, we have got atoms at twelve corners and an atom at the center of each of the two vertical hexagonal ends, which are this two and then three atoms at the center output here. So, here we can see that we have got three atoms at the center of a prism which is form by this triangular face. So, you got 6 atoms on the top, 6 atoms at the bottom, plus 2 at the faces over here.

Then, three atoms at the center or the middle plane of this prism which joints, the top hexagonal face and the bottom hexagonal face. All these make around 17 atoms for HCP lattice structure. The above lattice structure decides the number of slip planes in the crystal and this slip plane is a very important concept. This slip plane will decide lot of properties for this material. The slip planes are the directions within the crystal, in which the planes can slip or move easily one over the other. So, slip plane basically will decide in what direction the thing should move, the dislocation should move and this is what we have going to talked about.

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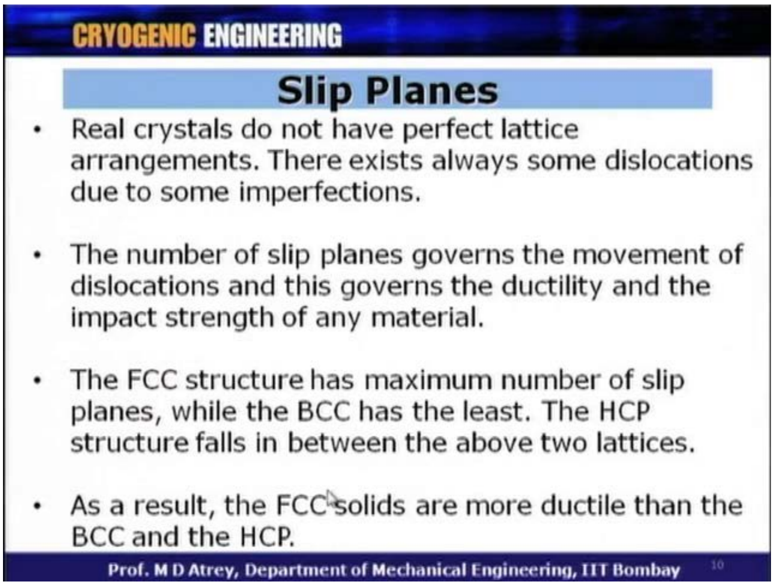

The real crystals do not have perfect lattice arrangements. The real crystal will have some kind of defect and dislocations and there exist always some dislocations like edge dislocations, cooled dislocations, some imperfections. Like, we got an additional atom, call insecticidal atom; we can have some atom absent which is called as vacancy etcetera and all the movement of this dislocation decide the properties of this material. The number of slip planes, now, the number of slip planes are governs by the lattice structure we talked about.

The number of slip plane, governs the movement of this dislocation and this governs the ductility and the impact strength of any material. Now, this all related, the lattice structure, the atom structure in a lattice, we determine how many slip planes are there. And the number of slip planes will allow the dislocation to move in the structure. So, ultimately, the lattice structure will decide whether a particular material allows the motions of the dislocations are not.

The FCC structure, what we found was FCC structure has maximum number of slip planes, while the BCC structure has the least. The HCP structure falls in between the above two lattices. What does this mean? It means that the FCC solids are more ductile as compare to the BCC and HCP. So, FCC we can call as the most ductile material followed by HCP, followed by BCC, based on the available slip planes in which the direction the dislocation can be.

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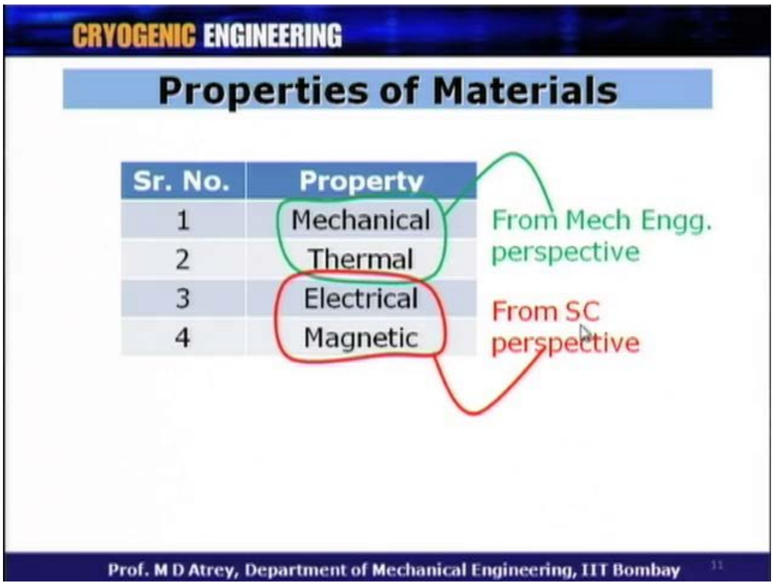

With this background, now, we will try to study various properties of material which are Mechanical properties, Thermal properties, Electrical properties, Magnetic properties. So, there are several of these properties which we can study, because this course is meant for mechanical engineers. I am going to talk about mechanical properties and thermal properties from mechanical engineering point of view. While, there are several electrical properties, several magnetic properties, which I think we will not bother about so much, while, I will cover these properties in terms of superconductivity.

So, we will devote some more time to understand, what are these mechanical properties? What are these thermal properties? Because that is what will govern, the thermal design of any material, thermal design of any cryostat, at the same time, thermal and mechanical design of any cryostat, for example, or any cryogenic equipment. While I will not cover these properties in details, the electrical and magnetic properties, but I will instead talked about superconductivity in this case.

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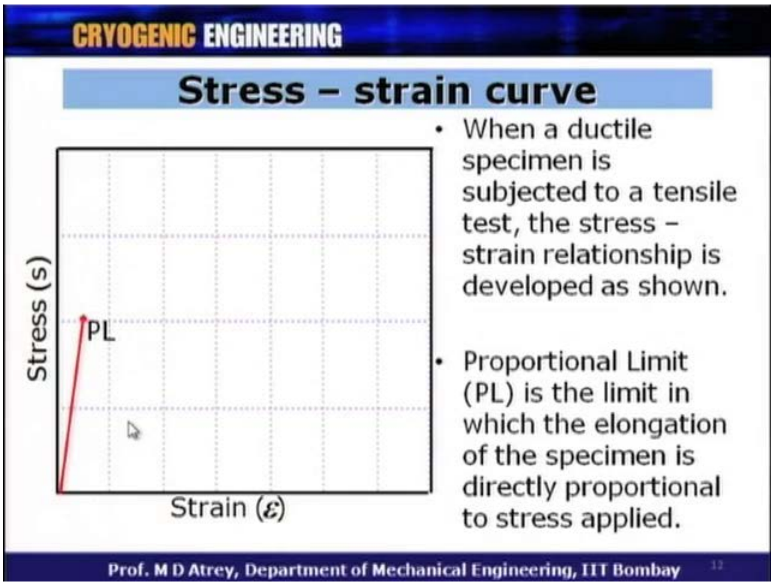

The mechanical properties can be well understood. Once we understand the stress-strain curve for any material, where the stress is kept on the y axis, while the strain is kept on the x axis. Now, when a ductile specimen is subjected to a tensile test, the stress strain relationship is shown as follows. So, you can see that in this case, the stress is varying in the relation with the strain and the variation is linear variation or we can say that, the stress is directly proportional to strain in this case. Now, you could see that, when the material is subjected to tensile, the loading, the stress is increased in a straight line up to the point called proportional limit or PL, which is what I have written here.

What is this PL? This PL is the limit, in which the elongation of the specimen is directly proportional to the stress applied. So, we can say that during this period, stress is directly proportional to strain. Most of you may have done this entire thing into data; I am just trying to give you some fundamentals. So, that, we can understand the variation of properties, which we are going to discuss in the next slides.

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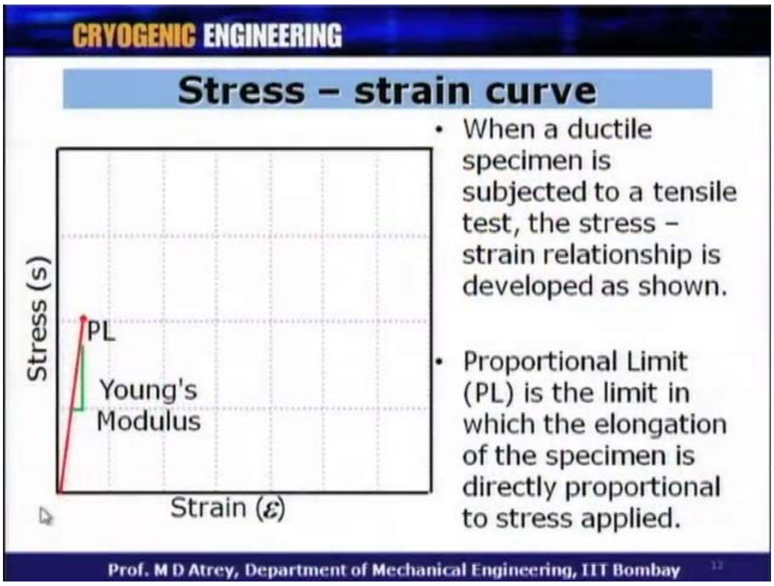

The slope of this line which constant during this entire line is called as you know young's modulus. So, stress upon strain is constant during this period.

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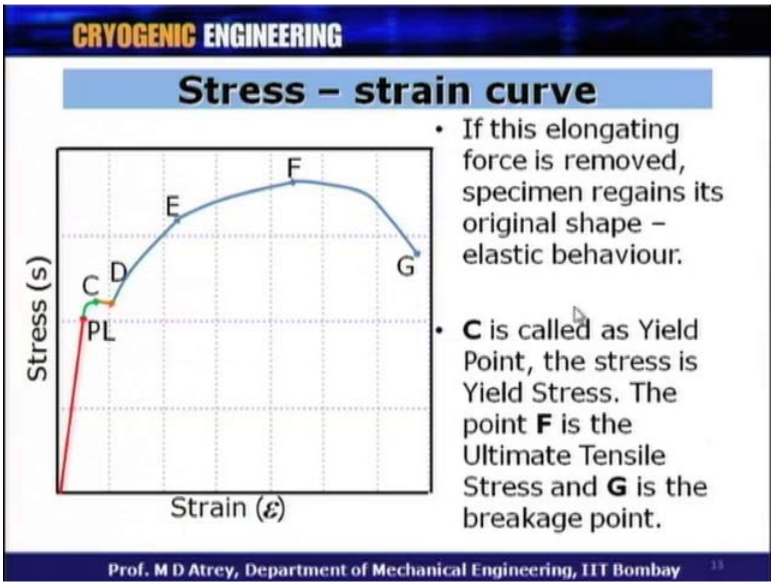

Now, if this elongating force is removed in this case, the material will come back to its original shape and size. And that is why, we call that this particular behavior is nothing but elastic behavior of the material. Even if you remove the elongating force, the material will come back to its original shape and size. However, if we apply the force beyond its particular strain and beyond its particular stress; you can see lot of different things happen. We can see first at this point, at point C, that there is a tremendous increase in strain immediately by the application of very small stress.

If we apply more stress or if we apply more force, we can follow the behavior in this pattern. This is what a stress strain curve of any ductile material would be. What you can see from this is, we can see the elastic region up to PL. We can see that the material yields during this place; this is called yielding and the material shows plastic behavior at this point. Now, during this period if the stress or the elongating force is removed, the material will not come to the original shape and size. You will find some deformation in the material.

Now, there are various points which are shown here C, D, E, F, G, the F what we call as ultimate tensile stress, the point C is called as the yield point and the stress is called as the yield stress, the value of the stress at this particular point is called as yield stress. While the point f we called is ultimate tensile stress, if increase the stress beyond this value, we find this kind of behavior and at this particular point G is the breakage point. In principle, the force at point G will be actually more than that of point F, but as you go beyond this point, the area cross section goes on decreasing.

Therefore, the force upon area or the stress starts coming. However, the engineering diagram will show that the G is more than F or this is what we call as the typical stress strain curve, for any material. And what is important to note here are, the two properties, one is the yield stress and other one is the ultimate tensile stress. We will study the behavior of these two properties at low temperature.

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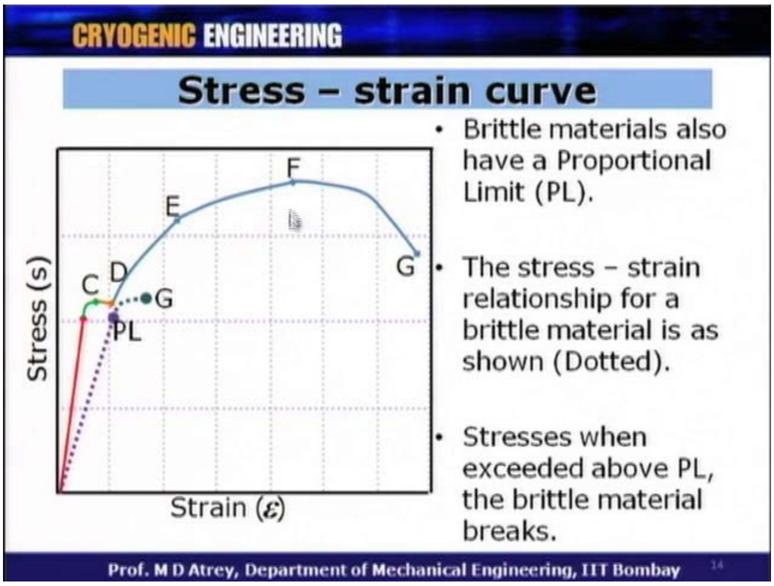

This is typical diagram for a ductile material and we can see now the brittle material also has a stress strain curve and it will also have its proportional limit. So, if I want to compute, if I want to draw a stress strain curve for a brittle material, let us say this is the brittle material, it will have its own proportional limit now during which time this behavior is an elastic behavior. If I increase the stress beyond this value, this is the behavior and G is the breakage point and the material will break.

So, a stress strain curve of brittle material is as shown over here and stress, when exceeds the PL value, it will break at this point G exceeds. So, in summary, we have a two stress strain curve; one is showing the ductile material and one is showing the brittle material. We will study the two properties more, that is the yields strength and ultimate tensile strength. What happens to this property at lower temperature?

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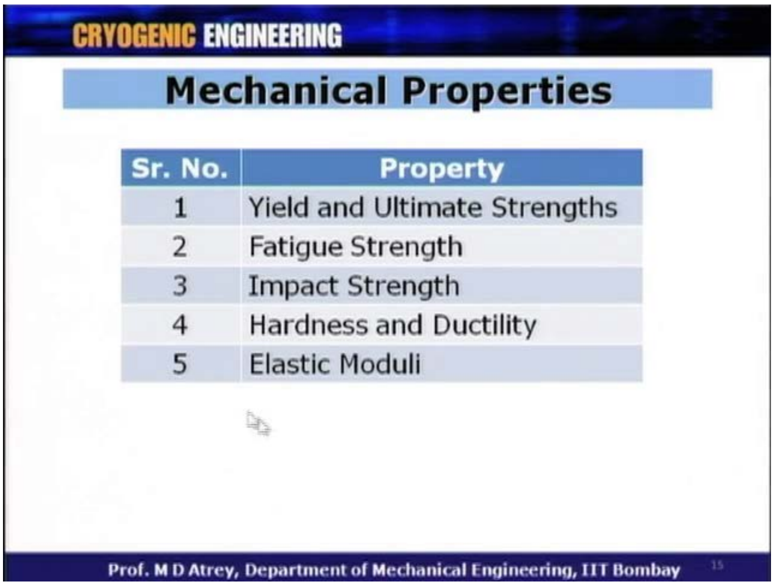

The mechanical properties which we want to study in this particular course are the yield and ultimate strength of which we just talked about. We talk about the fatigue strength of a material, we talk about the impact strength of a material, we talk about the hardness and ductility of the material and we talk about Elastic Moduli of the material. So, all these 5 properties in fact, 6 properties, they are basically the mechanical properties. In the next lecture, may be we talk about the thermal properties and the electrical property on the magnetic properties. Now, these are the five mechanical properties which we will discuss in this particular lecture for different materials.

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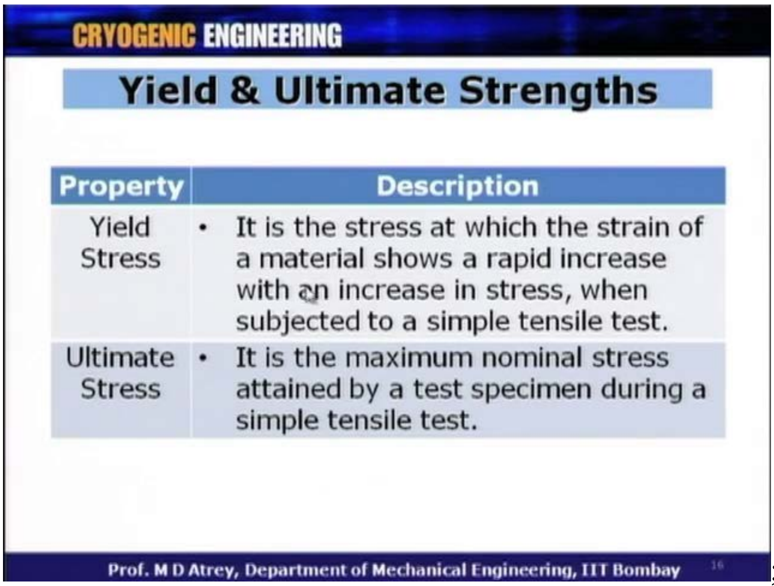

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First, we will come to yield and ultimate strengths of the material. Just to redefine those properties which we just saw, what is the yield stress? It does the stress at which the strain of a material shows a rapid increase with an increasing stress value. When subjected to a simple tensile test, we found that suddenly, the strain increased by giving a small stress at a particular location and that is called as the yield point and stress is called yield stress.

Ultimate Stress is the maximum nominal stress attained by a test specimen during a simple tensile test. So, ultimate stress is also a very important property a vary characteristic property of any material and also yields stress also is a characteristic of characteristics of a any material

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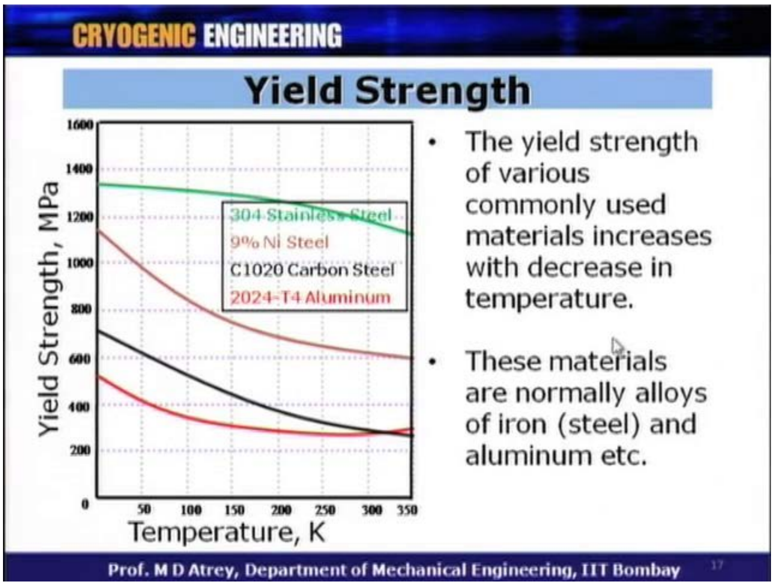

Now, we will study what happens to this property at low temperature? This particular figure gives the variation of yield strength at low temperature. You can see the y axis is giving the yield strength, while the X axis gives the temperature variation in the reverse direction; that means, what I am seeing here is a 300 Kelvin is a room temperature and in I am coming down towards 0 Kelvin or towards cryogenic temperature. What you can see? I have shown different curves here there meant for different materials. For example, this curve is meant for 3 0 4 stainless steel, SS 3 naught four, the second curve is 9 percent nickel steel, the third curve is carbon steel C 1020 and then we got aluminum alloyed.

All these vertexes are shown in this region in the order of decreasing the strength value. So, we can see that, in all these cases, the strength as if come down lower in temperature, the strength has increased most of the cases in all the cases almost, while the stainless steel shows maximum strength as compare to the other materials. So, we can conclude from this, yield strength of various commonly used materials increases with decreases in temperature; this is what we see from this particular curve.

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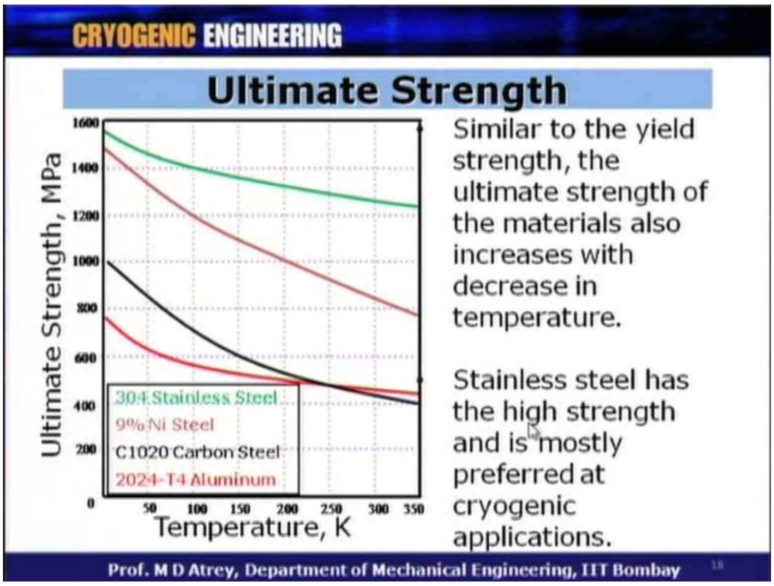

These materials are normally alloys of iron and aluminum etcetera. When we saw the curve it was for yield strength and now, sees the similar character of a curve for ultimate strength. So, again in this particular map, what you see is an ultimate strength plotted on a y axis and again temperature on the X axis. And again you can see that, as a temperature is lowered from room temperature to 0 Kelvin, the ultimate strength of the material have increase, the way it was shown for yield strength. So, we can see that in both the cases, the yield strength and ultimate strength increase as a temperature is lowered.

At the same time what we again can see from this, that the stainless steel shows maximum ultimate strength in this four materials followed by 9 percent nickel, followed by carbon steel, followed by aluminum as shown in the order in given in this region. So, again we can conclude similar to the yield strength, the ultimate strength of the material also increases with decrease in temperature; this is the very important thing. At the same time what it shows is, the room temperature is actually the uncertain thing if the material is safe at room temperature; that means it is definitely safe in the cryogenic temperature.

So, for any design we were worst design will be at room temperature, because your ultimate strength or the yield strength is lowest at room temperature. So, the safest case, if we want to see the failure mode, it should happen at room temperature as far as the failure based on ultimate strength and yield strength is considered. We could also from the two figures that stainless steel has the high strength and is mostly preferred material at cryogenic conditions. So, many applications what you see is having stainless steel as a material.

I have just got a small specimen over here you can see a very thin wall tube which has got around 0.15 millimeter thickness and this is the welded to a flange, what is constituting one tube and if I close from this side, if I got some welded structure at this point, we have use this tube for pulse tube cooling and we have seen that this particular tube of thickness 0.15 millimeter can stand at very high pressures and as high as 25 bar pressure of gas. It shows that such a small thickness of a material, also can stand very high pressure and in most of the application.

Therefore, what we have use is stainless steel which is SS 3 naught four, we use it stands very high as higher 30 to 35 bar also. One has to really calculate the hooks stress in this case and then calculate dimensions of this, but a thickness of 0.15 to 0.2 millimeter or 0.3 millimeter can stands very high pressure. I just bought the specimen to show you that such a small thin wall tube can stand very high pressure SS 3 naught four is the material, which is being used for this particular purpose right. Going back from having study this ultimate strength behavior and yield behavior at low temperature let us try to understand why it happens like this?

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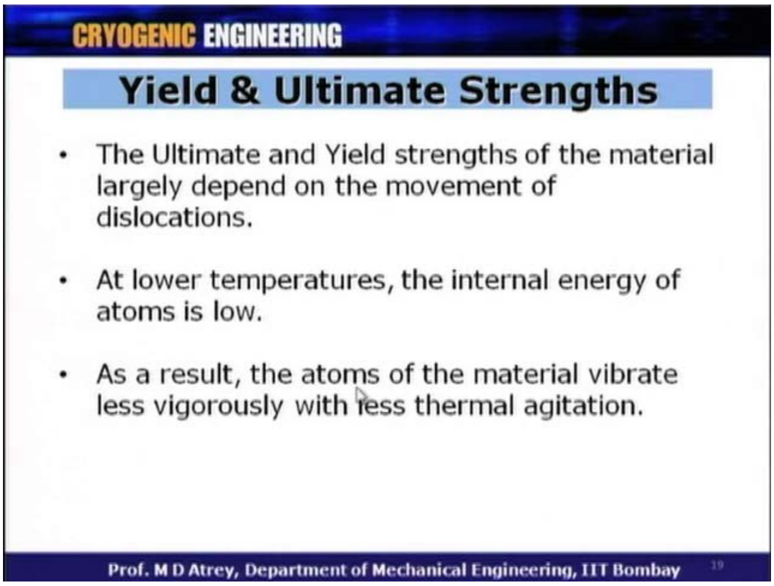

Ultimate and yield strength of the material largely depend on the movement of dislocations. We have earlier studied the movement of dislocations, and its relations with the slip planes and its relations with the lattice structure. The movement of dislocation also depends on the internal energy or the lattice vibrations, and at lower temperatures, the internal energy of the atoms is very much low.

As you know, the internal energy is basically a function of temperature and if the temperature is low the internal energy of the atoms also is low. As a result, the atoms of the material vibrate less vigorously with less thermal agitation. So, at lower and lower temperature, the vibration the lattice vibration is very very minimum and therefore, the material vibrate less vigorously with less thermal agitation.

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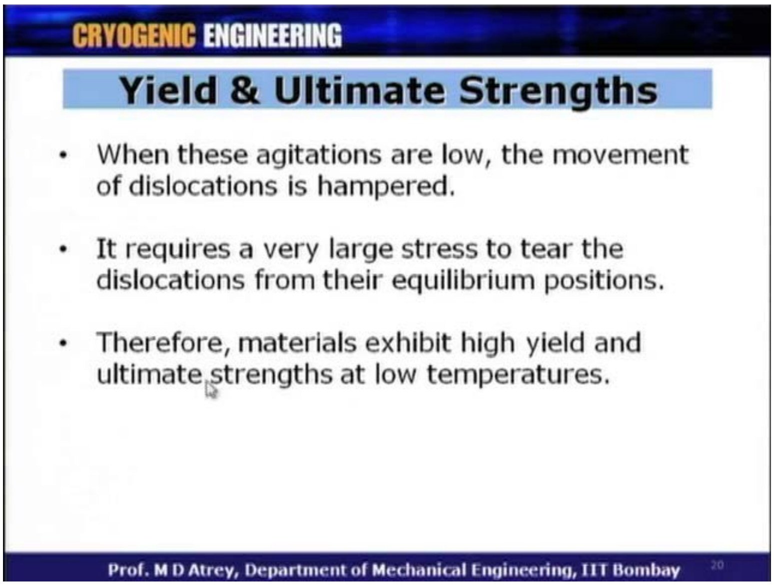

When these agitations are low, when these agitations are low at low temperature, the movement of dislocation is hampered. You can imagine that, when the dislocation movement is ultimately it may be a long dislocation movement, a very large dislocation movement at room temperature; however, at lower and lower temperature, the motion has come down and this vibration if they are reduced, it does not allow the dislocation to move, it will hampered the movement of the dislocation when the movement of the dislocation is hampered. What will have to do? This dislocation movement now will require a very large stress to tear the dislocations from their equilibrium position.

If we want move the dislocation now, when the thermal vibrations are very large or the lattice vibrations are very large, we will require very large stress to tear this dislocations from their equilibrium position, which means that the material will exhibit high yield and ultimate strength at lower temperature. So, the behavior of the material at low temperature in terms of increased yield strength and increased ultimate tensile strength at low temperature could be understood by this particular analysis that, the vibrations are very very low at low temperatures and dishampers the dislocation movements at low temperature.

So, till now we studied the yield strength and ultimate tensile strength and variations at low temperature in cryogenics. We also have to study fatigue strength. What is fatigue strength? The material exhibit fatigue failure when they are subjected to fluctuating loads.

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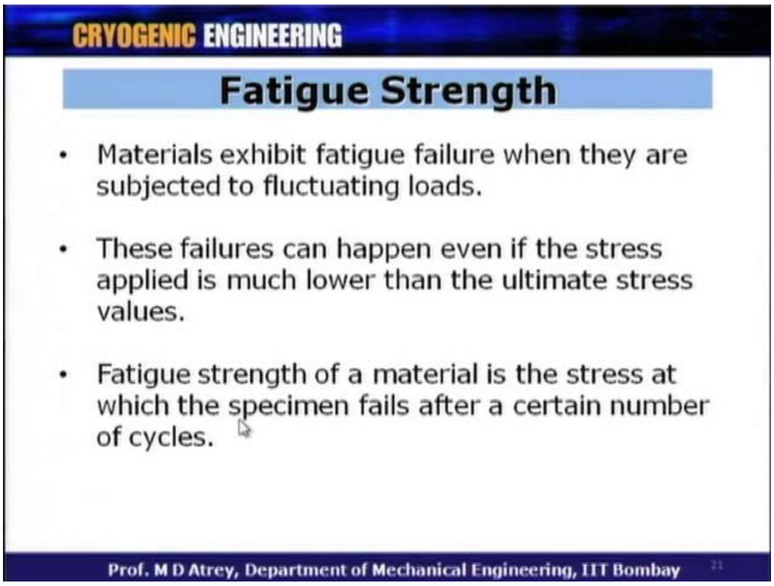

Now, this fluctuating loads could be, for example, I have got a small little sample over here, you can see that this small bearing through which the piston goes and as you know the piston is going to have an oscillating motion or a fluctuating motion up and down and this is called a flexure bearing and this particular bearing goes up and down and therefore, this will be subjected to fatigue failure if at all it fails it will fail back fatigue. So, at ensure that while designing this particular flexure bearing the stress achieved by this while in motion are less than a particular value or particular fatigue strength of this particular material.

This is very important that the bearing which is subjected to fluctuating load can stand the stresses generated during this motion. So, these failures can happen even if the stress applied is much lower than the ultimate value. This is very important, that the fatigue strength is actually much less than the ultimate strength of the material. So, one has to really compiled, one has to really understand the failure of this particular item will because of this fatigue, the failure for example, of this bearing is going to be because of fatigue and not because of tension or compression.

The fatigue strength of a material is the stress at which the specimen fails after a certain number of cycles. This is what a definition of fatigue strength is, that it is a strength at which the specimen fails after a certain number of cycle. So, fatigue strength is normally defined in terms of cycles 10 to the power 6 cycles, 10 to the power 8 cycles etcetera.

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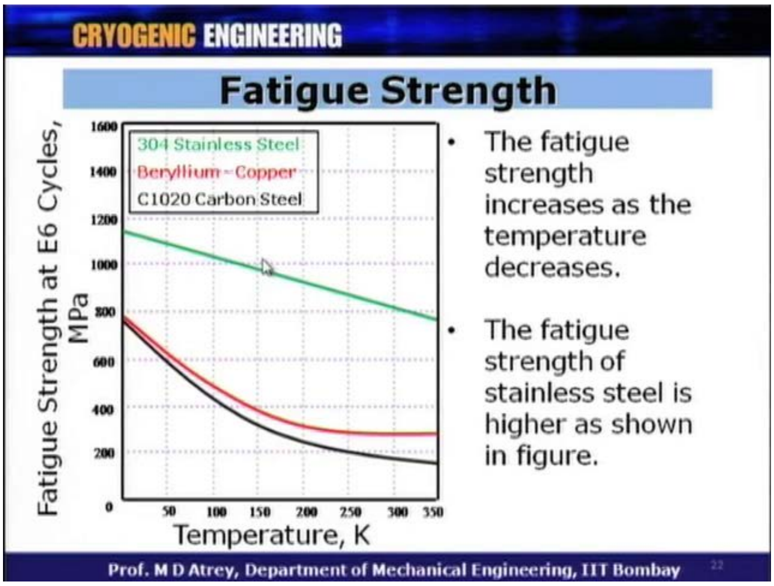

Now, let us see how the strength variation happens at low temperature. So, here again you can see a curve on the Y axis what we have plotted is fatigue strength at 10 to the power 6 cycles, E to the power 6 cycles over here, while on the X axis what we have plotted is temperature and this my room temperature at 300 Kelvin and this is where you move towards the cryogenic temperature range as you have seen earlier in the yield strength and ultimate strength variation. Again you can see that, as the temperature gets lower down the fatigue strength increases.

So, all the three cases these are the material which can stand fatigue strength, again we have got a stainless steel, beryllium copper over here and carbon steel. In all these three cases, what we see is at lower temperature the fatigue strength shows an increase over here. So, again the worst case for this material is at room temperature. So, we can conclude again the fatigue strength increases as the temperature decreases. So, as a temperature goes down toward cryogenic region the fatigue strength increases. The fatigue strength of a stainless steel is higher as shown over here. So, again we can conclude that stainless steel is preferred material, if it is going to be subjected to fatigue loading.

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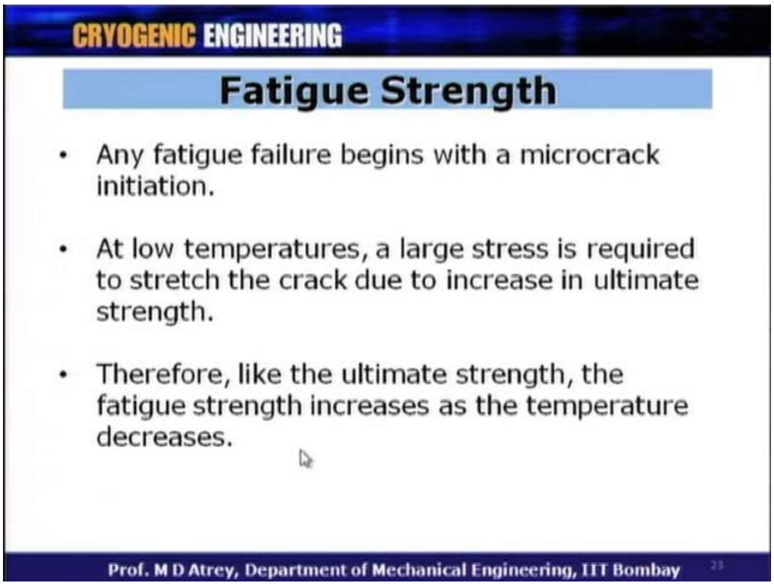

Now, any fatigue failure begins with a micro crack. Again, we will try to understand, why does it happens the way it is. We have seen that, the fatigue strength increases at lower temperature and any fatigue failure normally, it begins with a micro crack initiation and at low temperature after the initiation of a crack, we require a large stress to stretch this crack do we require a large strength because the ultimate strength of the material has increased. So, at lower temperature, ultimate strength increases.

Therefore, the crack stretching or the crack propagation the crack initiation is, but the crack propagation or crack stretching, the stress require for this is going to be a very large because of the increase in ultimate strength of a material and that is why, like the ultimate strength, the fatigue strength also increases at lower temperature or as the temperature decreases.

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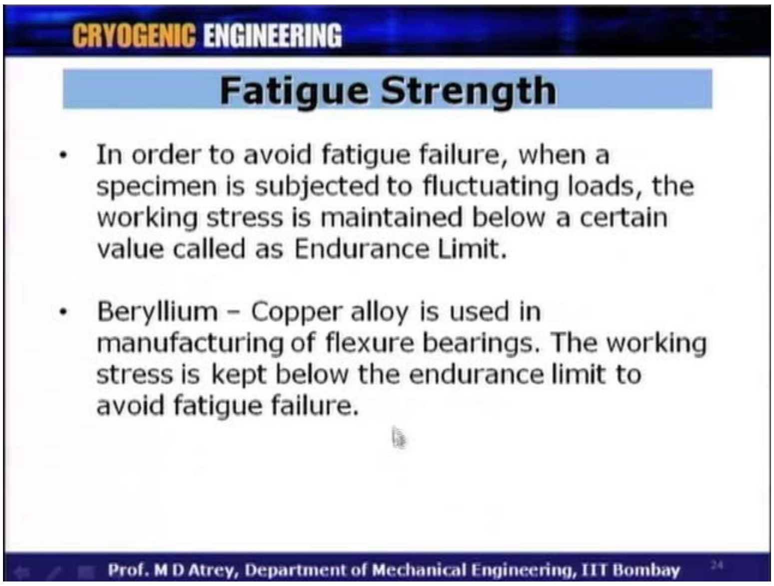

Now, in order to avoid fatigue failure when a specimen is subjected to fluctuating load, the working stress is maintained below a certain value called endurance limit. So, if I want to worry about a certain failure, which I know that it is going to happen due to fatigue, what I have to worry about is not the fatigue strength, but I should worry about endurance limit. If I keep the value of the stress generated below the endurance limit; that means, in principle this material should never felt and therefore, the endurance limit of a material is very important.

The property we should know the endurance limit of the particular material which is going to be subjected to fatigue loading and I should ensure that the stresses generated are less than this endurance limit. The flexure bearing which I showed to you is made out of beryllium copper alloy. So, here you can see a beryllium copper alloy and this is what we call as flexure and this is what is use to manufacture the flexure bearing. The working stress is kept below the endurance limit to avoid fatigue failure. So, I should know the endurance limit of the beryllium copper alloy and I should keep the stress is generated below the endurance limit of this particular material which will ensure that this particular material will never fail by fatigue.

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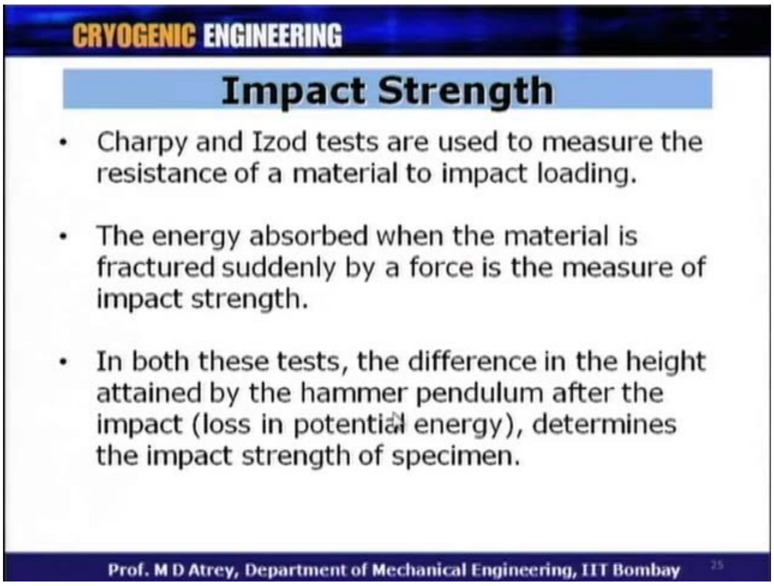

Now, let us come and discuss regarding impact strength and ductility of the material, these are very important characteristics. We have various states which we have or in material science that charpy and Izod tests are conducted in order to measure the resistance of a material to impact loading. So, a certain material, we know that it is going to be subjected to impact loading that is sudden loading, we conduct this two tests charpy and Izod tests from where we understand how much that material is resistance to impact loading. Major of resistance is basically nothing, but the amount of energy absorbed.

The energy absorbed when the material is fractured suddenly, which means impact loading by a force and this is the major of this impact strength. How much energy it can absorb after the fracture? If the material is fractured, how much energy it can absorb will basically determine the impact strength of the material more the energy it can absorb it has got more impact strength. In both these charpy and izod tests, the difference in the height attained by the hammer basically, in these cases what you have is a hammer which comes down from determined height, it hits the material and it fractures the material and this hammer goes beyond the material.

So, depending on the height which this hammer attains after the fracture is basically determine the impact the material. So, in both these tests the difference in the height attained by the hammer pendulum, after the impact that basically it losses potential energy this determines the impact strength of a material and this nothing, but the amount of energy the material can absorb after the fracture.

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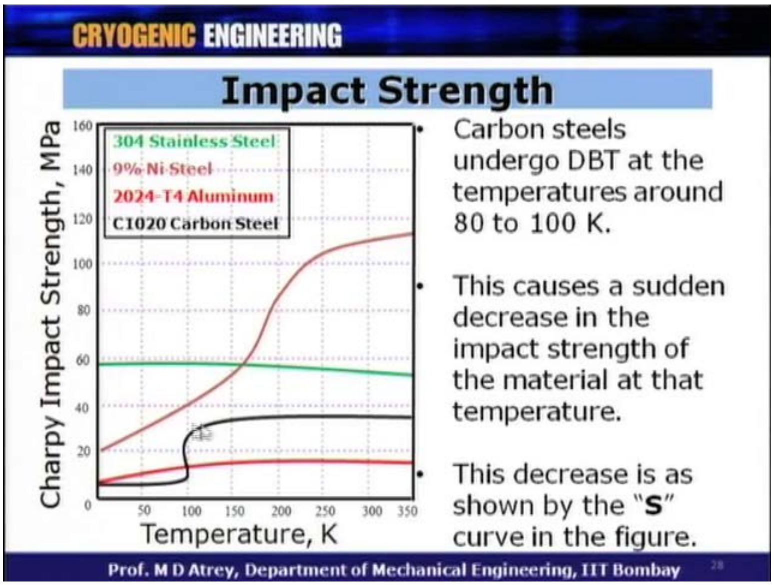

Now, this is the very different curve as compared to what you saw earlier. Here we got charpy impact strength on a Y axis and what you see on the X axis is the temperature again. So, again we see from room temperature and come down to cryogenic temperature. Now, here when we know that a particular material is going to be subjected to impact load, we have to check that that the impact strength of a particular material is high enough.

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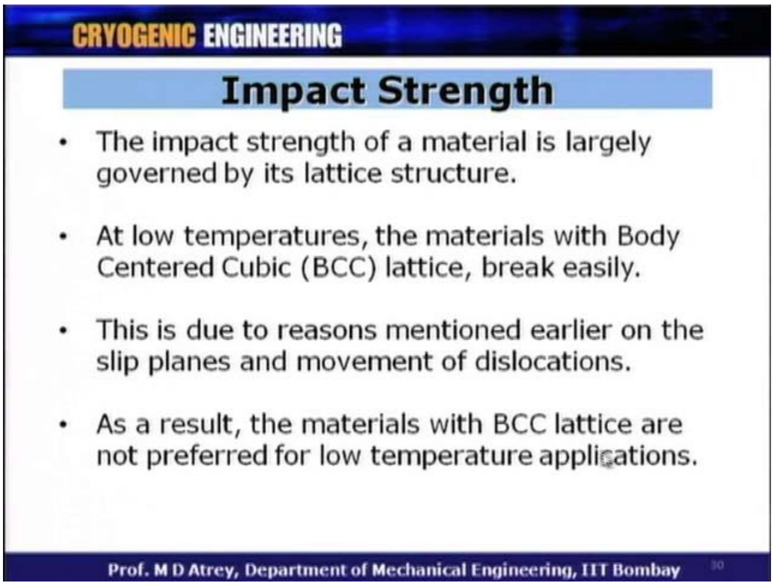

So, you can see different curves here and in general for example, you see that this is coming down, this is coming down, this is coming down, while for this particular material, which is stainless steel is almost horizontal. That means, there is not much variation in the strength value with the temperature. So, in general what you can say from this the impact strength of the material decreases with decrease in temperature or at most it remains constant for a particular material which is SS 3 naught four, while for all the material, the impact strength has come down. So, as the temperature gets reduce the impact strength of the material, does get reduce?

Now, this is the very funny curve in this and this a particular curve I would like to highlight your attention and this material show some very specific characteristic, few of the materials exhibits ductile to brittle transition for DBT at low temperature. So, you can see from this particular curve, does this material can be called as a ductile over in this region? Or it has high impact strength in this region. While at this temperature around 100 Kelvin it suddenly came down, the impact strength came down and came down to a very low level and it is, we can say that it is no more impact strength has drastically come down; that means, may be this material was ductile in this region.

During this temperature range and suddenly it has become brittle in this temperature. It has undergone a D B T or a ductile to brittle transition in this temperature region that is what we called as, while it does not happen for stainless steel it is happening for carbon steel. So, carbon steel basically undergoes ductile to brittle transition at low temperature and the temperature at which this transition happens this D B T happens is called ductile to brittle transition temperature DBTT and this DBTT for carbon steel around 80 to 100 Kelvin. So, carbon steels undergo DBT at the temperatures around 80 to 100 Kelvin.

This causes sudden decrease in the impact strength of the material as I just said, this is having high impact strength over here, while the impact strength are drastically came down at this point. Similarly, for 9 percent nickel the impact strength was very high here; impact strength suddenly comes down at lower temperature. While what we can see from here is, the impact strength of stainless steel remains unchanged at lower temperature, it is deputy variation the way it looks it is called as sometimes s transformation or s curve. So, this decrease is as shown in this s curve, many literatures refers this as also s transformation or s curve existence foe this particular materials.

So, this s transformation happens that 80 to 100 Kelvin in this particular material. Hence, these materials cannot be used for cryogenic applications. So, for all those materials which have got s transformation, which have got DBTT, which has got DBT they cannot be used in cryogenic application because at lower temperature they do not have any impact strength. Again, we can find from the curve that stainless steel is the most preferred material from the impact strength point of view. This is a very important finding from this curve.

The impact strength of a material is largely governed by its lattice structure. At low temperature the material with body centered cubic lattice break easily; that means, BCC which have got minimum slip planes it breaks easily because the dislocations cannot move in this case. This is due to the reasons mentioned earlier, on the slip planes and movement of dislocations. As a result the materials with BCC lattice are not preferred for low temperature applications.

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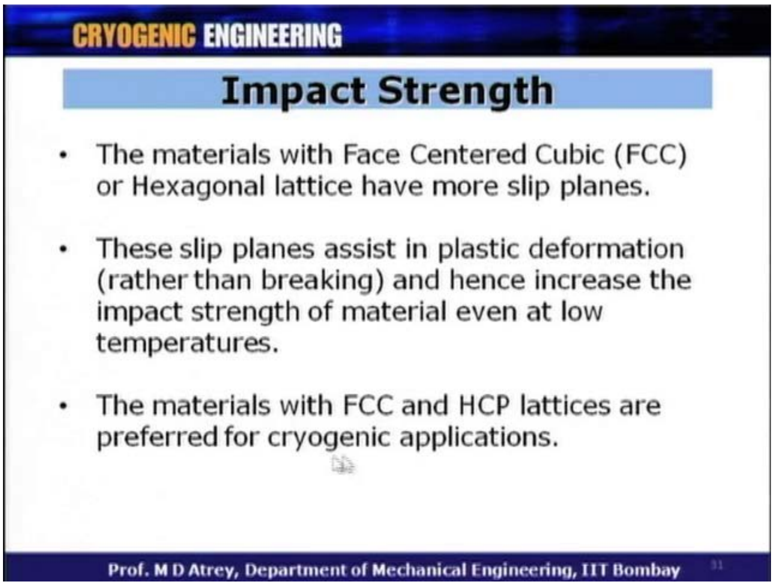

The material with FCC or hexagonal lattice have more slip planes and these slip planes assist in plastic deformation, as we know that dislocation can easily travel through FCC materials, through HCP material and hence increase the impact strength of material even at low temperatures. As a result, the material with FCC and HCP lattices are preferred for cryogenic application, while the BCC material that the carbon steel are not preferred for cryogenic application because they become completely brittle at low temperature or they impact strength is very very low at low temperature.

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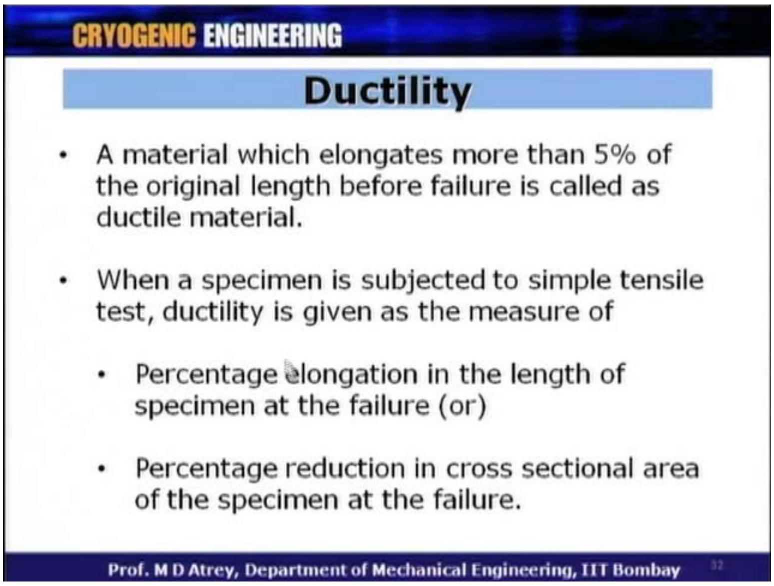

Now, let us see the next property which is Ductility, which is in a way related to the impact strength, what we studied just now. A material which elongates more than 5 percent of the original length before failure is called as ductile material this is the clear definition of a ductile material, which material can be called ductile. When a specimen is subjected to simple tensile test ductility is given as the measure of percentage elongation of the length of the specimen at the failure or the percentage reduction in cross sectional area of the specimen at the failure. So, basically percentage elongation or percentage reduction in cross section area will determine, whether a particular material is ductile at a given temperature or not. We will call percentage to study the ductility of a particular material.

Again, this curve shows similar curve as we saw earlier, that is the impact strength and this gives percentage elongation before failure verses temperature on the x axis. As you can see as the temperature gets reduced the percentage elongation decreases. So, this is for stainless steel, this is for nickel, this is for carbon steel and this is for aluminum. In all the cases what you see is, as the temperature gets lower, the percentage elongation gets lowered. So, again you have got s transformation for carbon steel, meaning which that it is, it cannot be use at low temperature while, the stainless steel, nickel steel and aluminum can definitely be used although the ductility is lower at lower temperature as compared to the room temperature.

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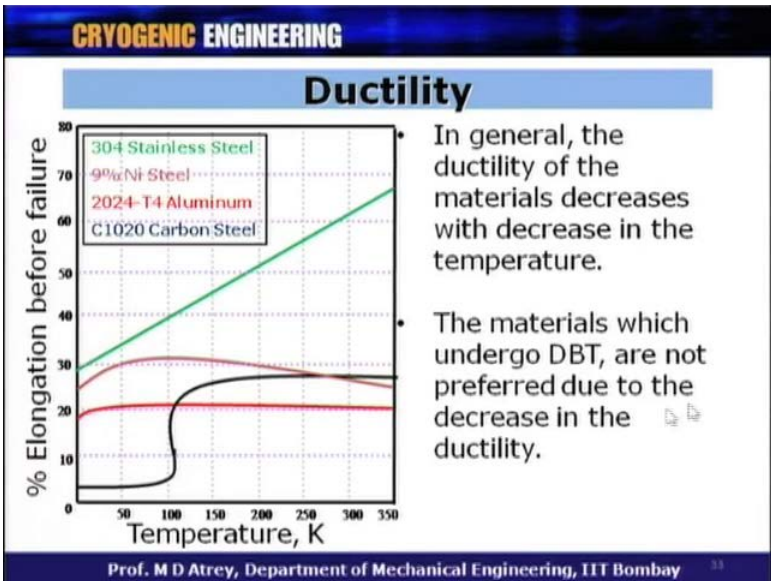

In general, therefore, we can say the ductility of the materials decreases with decrease in the temperature. The materials which undergo DBT are not preferred due to the decrease in ductility; that means, materials like carbon steel cannot be used at low temperature, because there are no more ductile at low temperature. For stainless steel, the percentage elongation is around 30 percent at this point you can see. At 0 Kelvin what we have is a 30 percent percentage elongation at 0 Kelvin, meaning that, it is fairly ductile for cryogenic applications.

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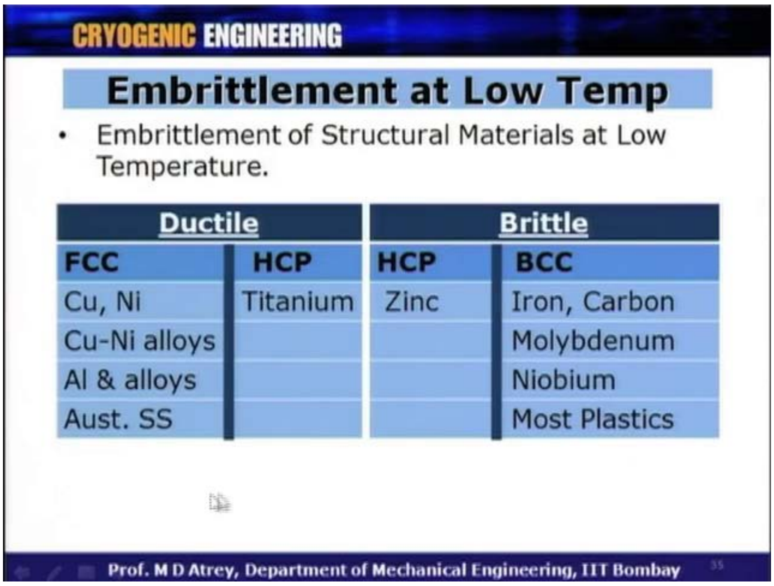

In summary, what we can see here is a different material the embrittlement at low temperature for different material and under ductile, what you see is a FCC and HCP can be used, while in brittle material also, there is some HCP material and all the BCC material. So, under ductile material, we can use most of the FCC material which is copper, nickel, copper nickel alloys, aluminum and alloys and austenitic stainless steel. The HCP material which we can use as a ductile material is titanium. So, all these materials can definitely be use for cryogenic temperature, provided satisfied other requirement like ultimate strength and yield strength etcetera depending on the failure mode for those particular materials.

While, these are all material which are brittle, which remain brittle at low temperature and therefore, they cannot be use unless specifically required and specifically evaluated at lower temperature. But mostly these materials will not be use for cryogenic applications.

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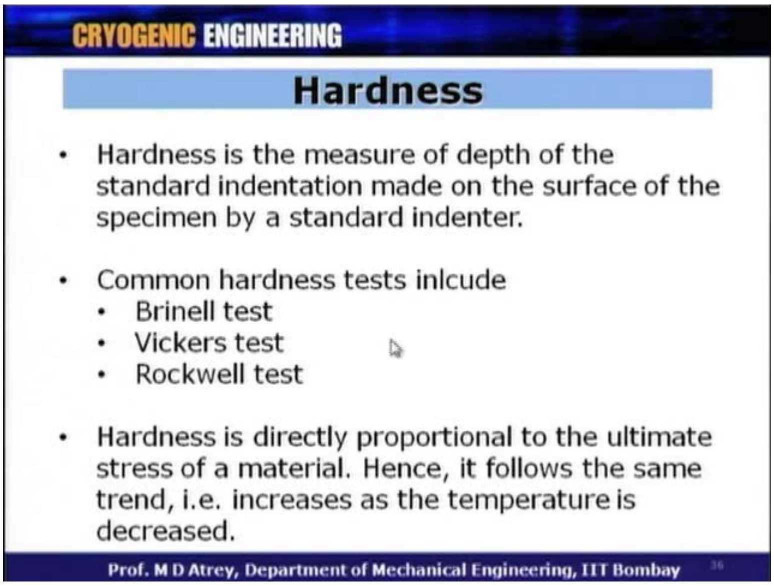

The next property is hardness, hardness of material. The hardness is the measure of the depth of the standard indentation made on the surface of the specimen by a standard indenter. Most of you have studied these that you have got standard indenter and you depth of these indentations. The common hardness tests include brinell test, Vickers test and Rockwell test. So, got a brinell test number BHN and VHN etcetera to determine or to measure the hardness number of a particular material. Hardness is directly proportional to the ultimate stress of a material.

And therefore, we know that, the ultimate of stress of a material increases at low temperature, meaning which we can conclude that, the same trend will be holding good for hardness also. That means, the hardness increases as the temperature decreases alright. So, we can conclude from here that the hardness of the material increases at lower temperature.

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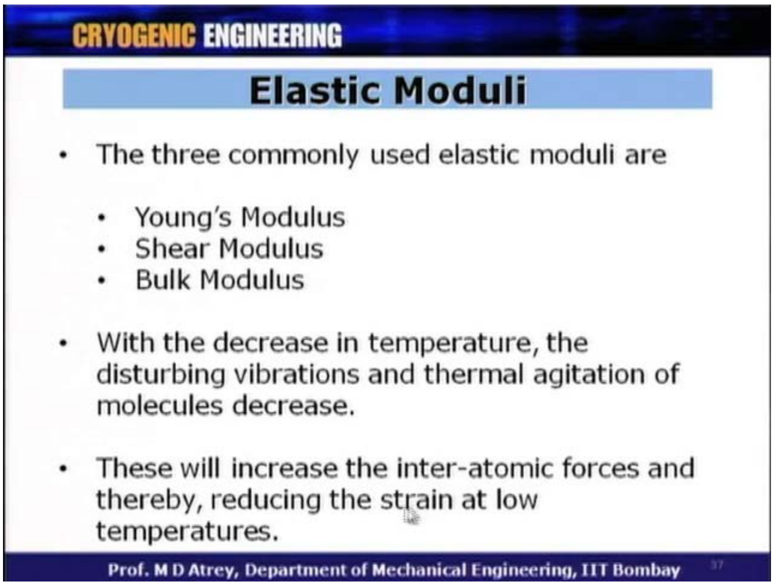

The next property is elastic moduli. The three commonly used elastic moduli are young's modulus, shear modulus and bulk modulus. Let us now going to the definition of the all these modulus, but we have studied the young's modulus for tensile stress as I shown in the earlier curves. With the decreasing temperature, the disturbing vibrations and thermal agitation of the molecules decrease, this is what we studied. Because all depend on the temperature of the materials at lower temperature the vibrations and the thermal agitation of the material will be less. These will increase the Inter atomic forces and thereby reducing the strain at low temperature what we mean to say that, at lower temperature the Inter atomic forces will be higher and therefore, strain induced will be low at lower temperature.

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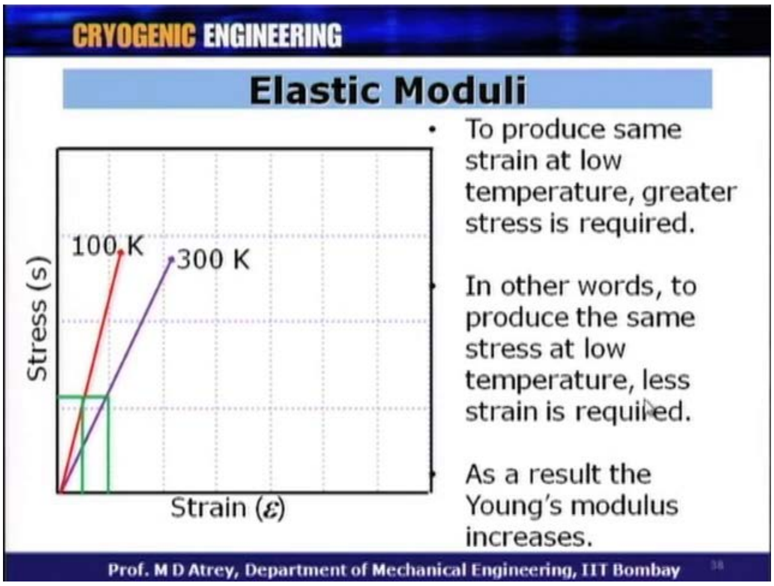

So, if I want to understand that thing, if I have plot a stress strain diagram for a material, a stress strain curve for a 300 k and at 100 Kelvin and if you see that, if I want to produce the same strain; that means, I have got same strain for these two temperatures, I will say that at lower temperatures, I get highest stress, as compare to at higher temperature; that means, the stress value for the same strain at three hundred K is much less as compare to what it is for 100 Kelvin. So, if I want to produce same strain at low temperature, greater stress is require meaning which stress upon strain at 100 K is going to be more than stress upon strain at 300 K.

In other words, to produce the same stress at low temperature less strain is required; I can go in a reverse way now, if I want to have same stress I will get less strain at 100 Kelvin and more strain at 300 Kelvin. So, my stress upon strain at lower temperature will be different than stress upon strain at higher temperature. What does it mean? The stress upon strain at lower temperature is more and as a result of which the young's modulus increases at low temperature because my strain values are less at low temperature for the strength strain.

So, stress upon strain at low temperature is going to be more as compare to higher temperature which means that, young's modulus will increase at low temperature and in the same way, I can conclude that this cur particular show that the young's modulus variation at lower temperature with the temperature variation. So, again you can see that, there is increase in the young's modulus at low temperature. The young's modulus of various commonly used materials is as shown in the adjacent figure. The elastic module increases with the decrease in temperature and all the three elastic moduli follow the same trend. So, we will not study the other entire moduli, but what we can understand from the young's modulus is at all this elastic moduli increase at lower temperature.

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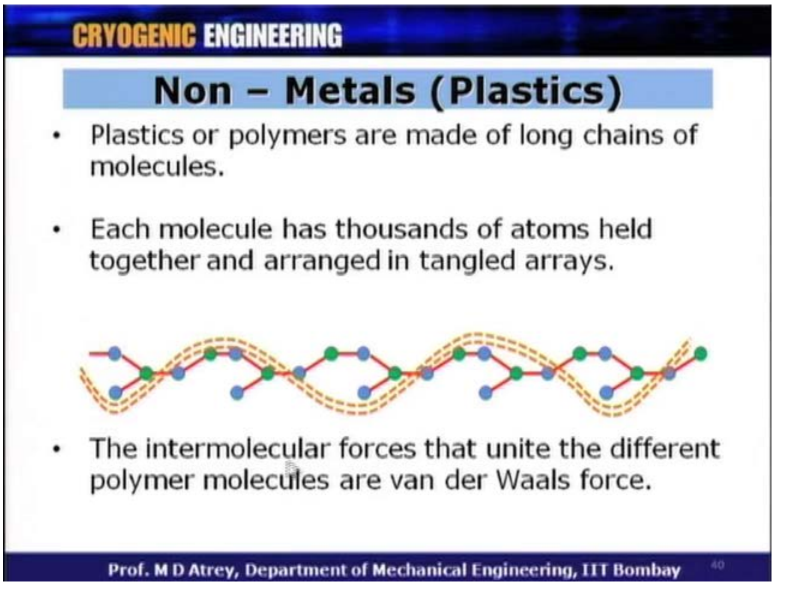

Having studied all these properties for metals, there are non metals also used as we talked earlier and the non metal which we want to study here is plastic. plastic or polymers basically plastics or nothing, but polymers are made of long chains of molecules that polymers are identified by the existence of long chain of molecules and each molecules has thousands of atoms held together and arranged in tangled arrays. So, this particular show, the various molecules and they are together with small arrays basically. Now, the intermolecular forces that unite this polymer molecule are very weak and there basically van der Waals force. This particular force keep them united together all the molecules are kept united because of this particular force.

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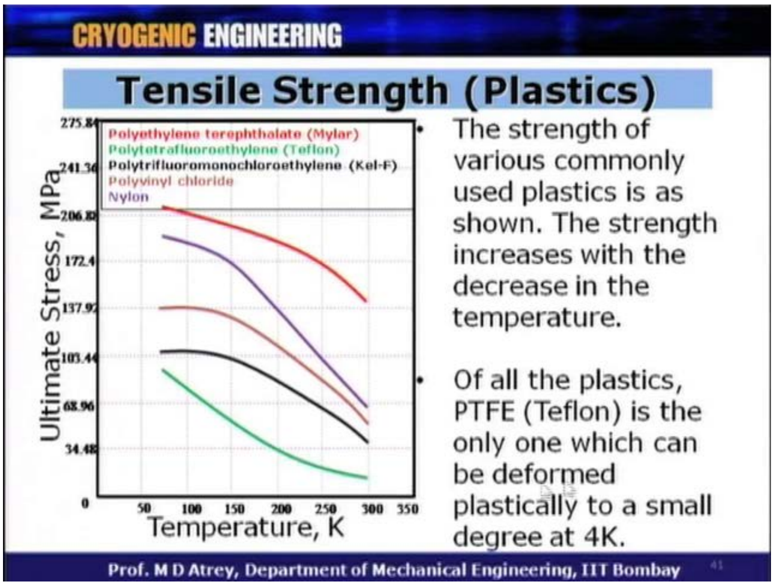

Now, if you want study the tensile strength behavior of plastics at low temperature, this particular curve shows this behavior. See if I want to plot ultimate stress of different plastics at low temperature, again, what you see is at low temperature the ultimate stress of this material increase. So, ultimate strength in the show increase and we have got a different material like Mylar Teflon which is nothing, but PTFE kel-F, nylon PVC etcetera. In all the cases what we have, the ultimate strength increased at low temperature. The strength of various commonly used plastics is as shown; the strength increases with the decrease in temperature, but of all these material, the most commonly use material in cryogenics in PTFE.

So, of all these plastics PTFE is the only one which can be deformed plastically because it retains it plasticity at low enough temperature at lower temperature around 4 Kelvin. So, the mostly used plastic in cryogenic is nothing, but Teflon or PTFE. So, as we saw earlier, that the mostly used material metal is stainless steel. Similarly, we can say that PTFE is the mostly use plastics in cryogenic application because it retains, it has got good strength at lower temperature, at the same time it retains it plasticity at lower temperature.

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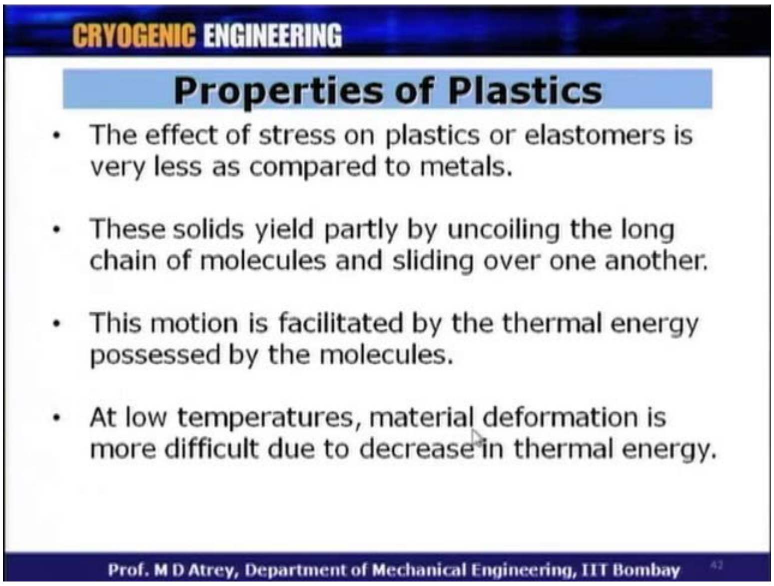

The effect of stress on plastic or elastomers is very less as compared to metals alright the metals show different behavior high stresses while the plastic do not show that because the yield partly by uncoiling the long chain of molecules and sliding over one another. The effect of stress actually does not shoe. So, much in case of plastics this motion is also facilitated by the thermal energy possessed by this molecules and at low temperature, material deformation is more difficult due to decrease in thermal energy. So, as you know that at low temperature, the deformation is not possible because of the decrease in thermal energy.

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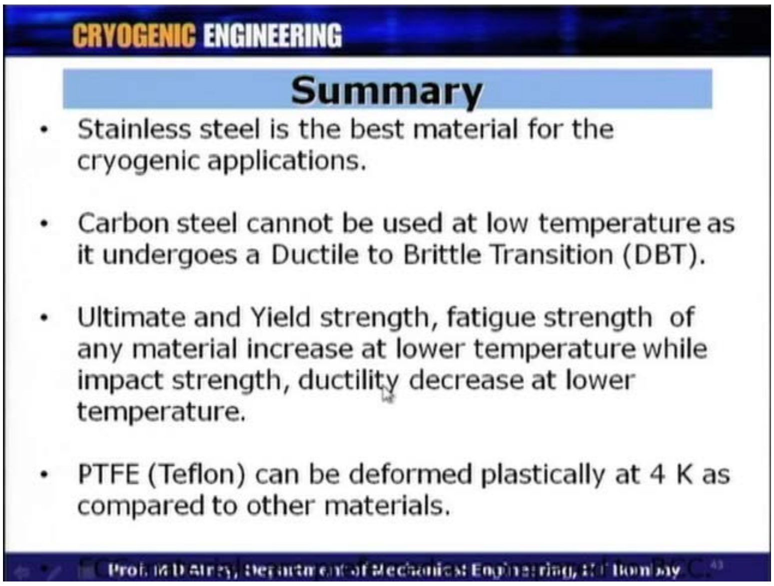

So, we talked in brief about plastics and we talk about at length about the mechanical properties of different metals. If I were to summarize the whole lecture summarize as follows. We found that stainless steel is the best material or the most preferred material for the cryogenic applications. Carbon steel cannot be used at low temperature as it undergoes a ductile to brittle transition, existence of DBT or DBTT ductile to brittle transition template.

We also saw that, the ultimate and yields strength, fatigue strength of a any material increase at lower temperature, while the impact strength and ductility decrease at lower temperature, they could still be acceptable for example, we saw that for stainless steel, the impact strength and ductility still acceptable at lower temperature. PTFE or Teflon can be deform plastically at 4 Kelvin as compare to other material and also therefore, PTFE is the more preferred plastic at lower temperature.

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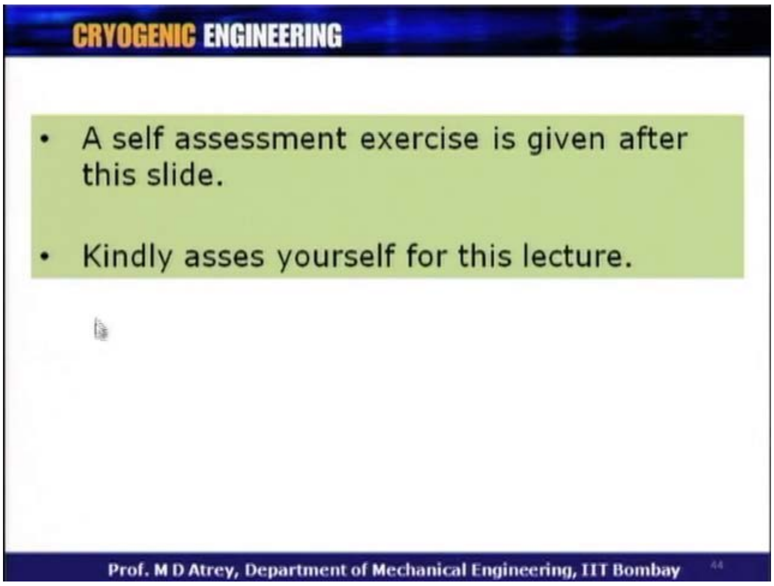

Again, we have got a self assessment exercise is given after this slide, kindly asses yourself for this lecture. So, we got around twelve questions for you. Please do self assessment for yourself honestly, and we given the answers also for those questions at the end. Thank you very much.