Advanced Materials and Processes
Prof. Jayanta Das
Department of Metallurgical and Materials Science Engineering
Indian Institute of Technology, Kharagpur

Lecture – 01
Introduction

Hello, welcome to NPTEL, today I will be teaching you Advanced Materials and Processes. Myself Jayanta Das and I am a associate professor at IIT Kharagpur, Department of Metallurgical and Materials Engineering.

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The research work I have done so far, is quite linked with this subject of metastable alloys, which are also advanced alloys.

Metallic glasses, nanostructured alloys, high entropy alloys, low stacking fault energy alloys and non-equilibrium processing of these alloys for their superior mechanical and magnetic properties.

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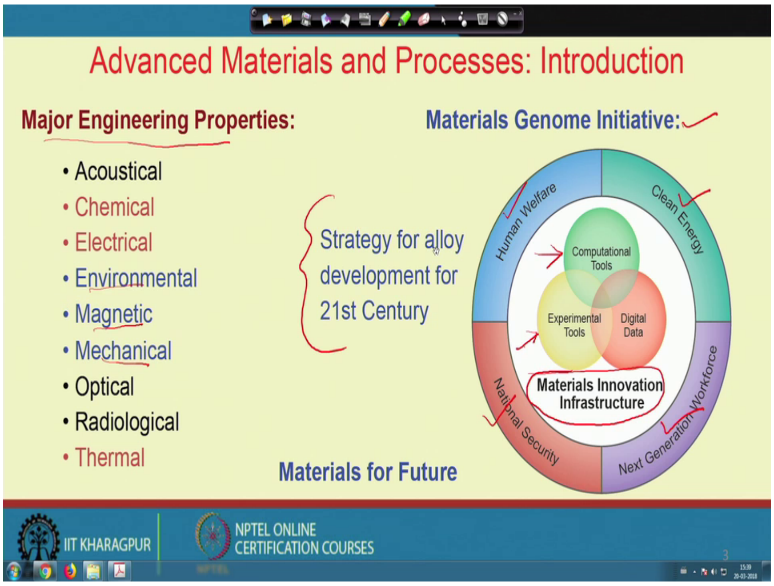

So, before going to the main subject matter, we first need to recapitulate some of the basic ideas. We as a metallurgist develop most of the alloys as per the requirement of the desired properties and here you can see the major engineering properties, which are acoustical, chemical, electrical environmental, magnetic, mechanical, optical, radiological and thermal. These are the nine engineering properties, which are very much important for designing any materials.

However, as a metallurgy background, we mostly concentrate on this blue colored written here, environmental means oxidation or any kind of degradation in an aqueous medium and magnetic properties and also the mechanical properties.

However, these are all these nine properties were selected and the material has been selected based on these properties so far, but in 21st century, the trend of choosing material has a major and many more consideration for selection. So, materials for future here the basic idea we keep all time the human welfare because of the human welfare we need to develop materials by considering a more cleaner energy and a more cleaner environment so that the material what we produce they should be recyclable as well as for taking into consideration of the national security and the next generation work force.

And this is a complete materials innovation infrastructure is going on, which is also often called as materials genome initiative. In this particular aspect whatever data we have collected as a engineer, as a researcher, we make them accessible to everybody and using many different computational tool, considering they are engineering properties or physical properties and also by interlinking different experimental tool, we like to develop materials and we also predict that by choosing some of the properties, we can target for getting a combination of many different engineering properties. So, this is a very innovative approach so, far going on, which is often called as a strategy for alloy development for 21st century.

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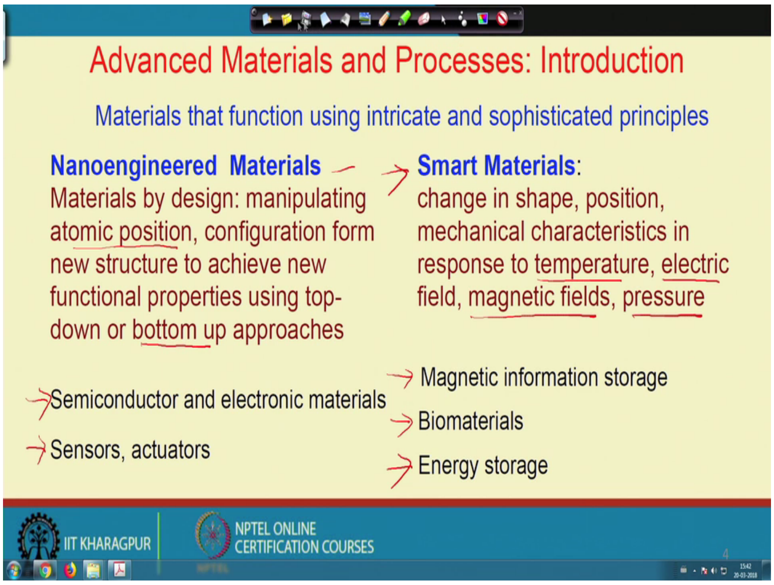

And here they are some important aspect we can see. So, the advanced material, what do you mean by these advance material? The material that function using intricate and sophisticated principle, this is somewhat a basic understanding on the advanced material. But in this particular course, we will be not only discuss some new materials, but the understanding on the used material and their advanced understanding, considering the research recent findings.

So, these recent findings, there are updated literature and we will be trying to gain some knowledge out of that.

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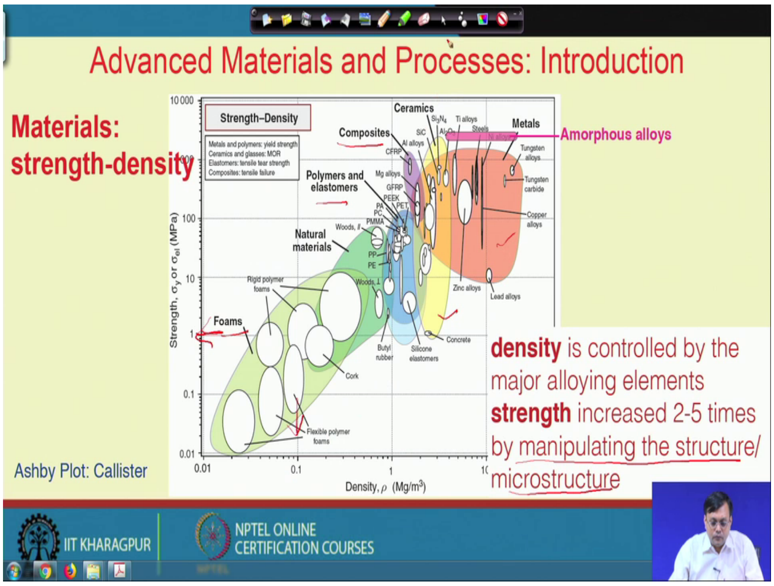

As an example, I can talk about let say nano-engineered materials and the nano-engineered materials here, the materials we often develop by design. what does it mean? It means by manipulating some of the atomic positions and configuration of the atoms, a configuration means an atom and surrounding there are many atoms.

So, this particular configuration whether it is FCC packing, whether it is HCP packing and whether it is BCC packing or any other kind of packing we can develop newer structure in order to achieve some new functional properties using either top down approaches or bottom up approaches. Here top down approaches means that we have a bulk material we keep on processing this alloys in order to tune the structure in the atomic scale.

Whereas, the bottom up approaches means that, when we start with atom or molecule and keep on depositing in a substrate and developing and making them to grow to make a bulk solid. So, this is called the bottom up approaches; however, there are many materials for let say for semiconductor electronic materials, sensors and actuators magnetic information storage and biomaterial energy storage and so on.

So, there are so many materials that are keep on developing day by day and by some dedicated researchers.

So, these all are under the category of advance material, one also important thing here is the smart materials. What is really a smart material means that, the material itself change its shape, position or let say mechanical characteristics, when we change some temperature parameter, some electric field is given to the material some magnetic field may be given or let say pressure.

And so, if you change any of these parameters, then material give a different response and these are often called as smart materials. So, as an example I can tell you like a shape memory alloy, which is a very well known smart material and in this material if we provide some mechanical stress and again if we give some temperature, the material can remember its shape. So, this is a very smart material and so on.

So, there are so, many a different objective of this particular course; however, will be limited to the 30 hours of lecture and let say if we first consider a very typical Ashby plot. And we know that a materials all the materials in our in our world can be classified into three major categories.

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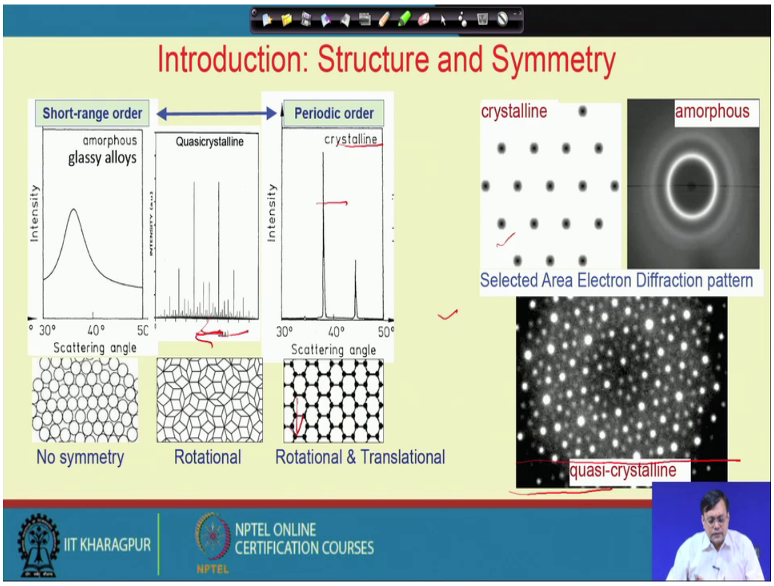

So, one is basically the metals or alloys and the other one is the ceramic, because of the bonding nature we can classify three different category of materials and another one is the polymer.

And these three different class of materials, if we combine them any two of them together we call them as composites. However, we can also produce some composite by mixing any of this material with some air. So, like a foam or let say some foam made out of polymer and air bubble. So, these are really very low density, you can see the density is almost like 0.1 milligram per meter cube; however, at the same time the strength is also very less.

On the other hand, the metals, metals are sitting almost at the higher density side also at the higher strength level. So, if you have a very closure look to all these different region that is occupied by this three different class of materials, we really cannot tune too much because metals has a range of density and range of a strength whereas, ceramic has a strength range and density.

So, the density is mostly controlled by the major alloying elements in case of a metal. However, the strength that can be increased to almost 2 to 5 times, if we can manipulate the structure and this is very important aspect of developing some next generation materials. So, this is a typical Ashby plot taking from Callisters book. So, however, at the same time, we can think about all the different structures that are available.

So, any material that possesses basically any of this three structures that is shown here.

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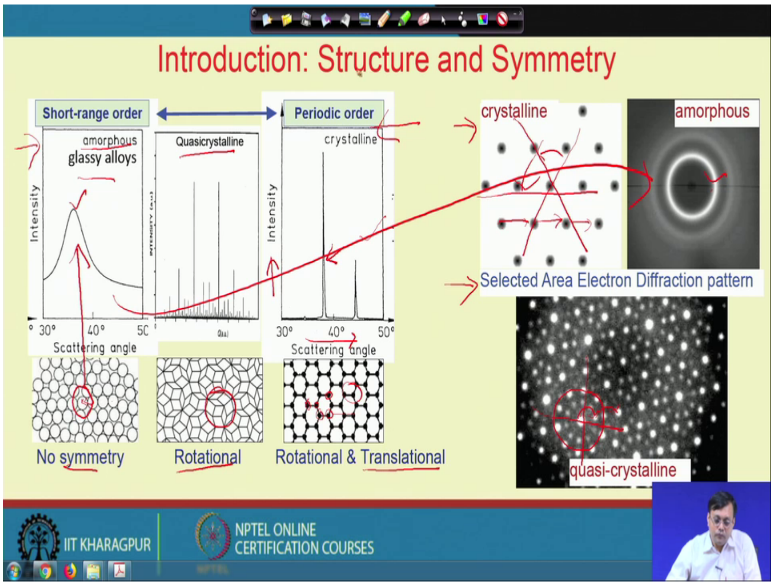

So, when we think about the periodicity of the atom we call them as a crystalline structure. Here long range periodicity exist whereas, if the periodicity does not exist at all, we have some short range order, let say we can assume some of the atoms and the nearby atoms that basically gives you such kind of peak actually.

This is a X-ray diffraction pattern, 3 X-ray diffraction patterns are shown here. So, here you can see this is an atom, this is another atom, this is the next atom and so on. So, we have a long range periodicity, which will give you such kind of a very sharp diffraction peaks. So, here this is the scattering angle versus intensity and you can generate this plot under x ray diffraction using Bragg's law.

So, here if you have a very clear look, then we have basically some translational symmetry. So, there is a symmetry exist. So, atoms are basically sitting at a particular or fixed distance whereas, here the atoms there is no fixed position and they are randomly distributed. So, these alloys are materials often called as amorphous material in case of alloys, we called is as a glassy alloys.

At the same time, here there is no symmetry exist and here we have both translational symmetry means periodicity of the atom as well as there is a rotational symmetry. But in case of a quasi-crystalline structure we only have rotational symmetry, here you can see the rotational symmetry exist.

If we take any of these three materials and then we go for some transmission electron microscopic studies and there is a purpose called let say information we can collect from selected area electron diffraction pattern. So, this is a typical diffraction pattern from a crystalline alloys, here you see both the periodicity exist.

So, with the particular distance, the reciprocal lattice point are appeared in the selected area diffraction pattern. So, this is translational symmetry, at the same time we can easily see that there is also a rotational symmetry exist ok. So, if you rotate this structure then it is a symmetric one.

Now, on the other hand if you look at this kind of amorphous alloys, then we will get such kind of selected area diffraction where you will get only amorphous halo, because there is no fix periodicity of the atoms and the distance is varying.

So, we will get this first alloy, which is somehow linked with this, this is the first alloy to a link. Now, on the other case, the quasi-crystalline alloys, here we can see only the rotational symmetry. So, here we can only see the rotational symmetry, but there is no translational symmetry.

So, this particular distance always follow the Fibonacci series ok. So, the distance is linked with the Fibonacci series only.

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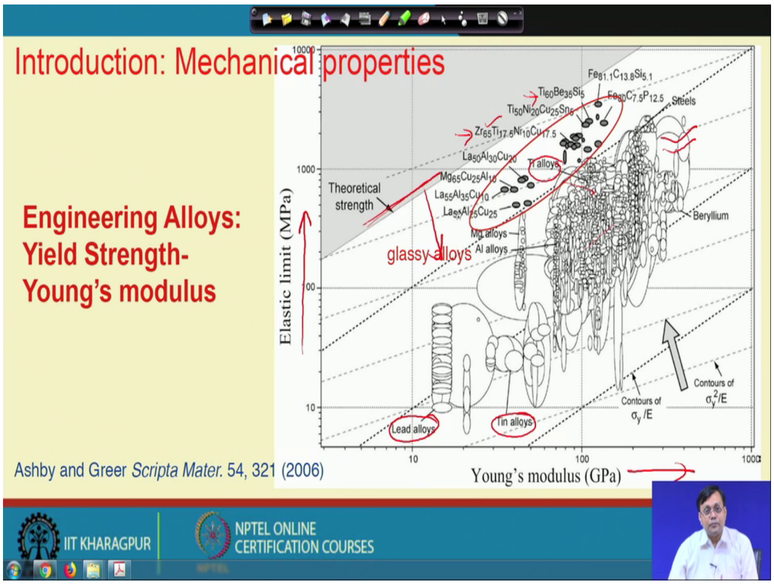

Now, once again why we are talking about the structure, because the structure and the properties are very much will linked and that is why we always a metallurgies, always look for it structure in order to interlink the properties. Now, another very simple Ashby plot if we look at here, this is an elastic limit which basically means a yields strength versus Young's modulus plot.

And here you see that the conventional engineering alloys like lead alloy or tin alloy or let say the other titanium alloys and so on, here the titanium alloys is this, they are all are occupying some space in this in this map and the higher the Young's modulus, the higher the elastic limit. Elastic limit means yield strength in megapascal.

So, here steel is almost a dominating here, even though the theoretical limit is lying here. The theoretical strength means basically a crystal without having any dislocation or any defect, the material show some strength and that is the theoretical strength, that is extremely high. But that strength basically decreases a lot because of the presence of defect like dislocations, dislocations is one of the defect. However, if I take the same plot and put the glassy alloys, like here some titanium based glassy alloys, some zirconium based glassy alloys and these are all the glassy alloys and here are the point. So, they are almost close to the theoretical limit.

Because this glassy alloys do not have any dislocation and they are showing much more higher strength level then the conventional steels. So, one can conclude that definitely for mechanical strength purpose, one can use this conventional, one can replace some of this conventional steels with the advanced alloys.

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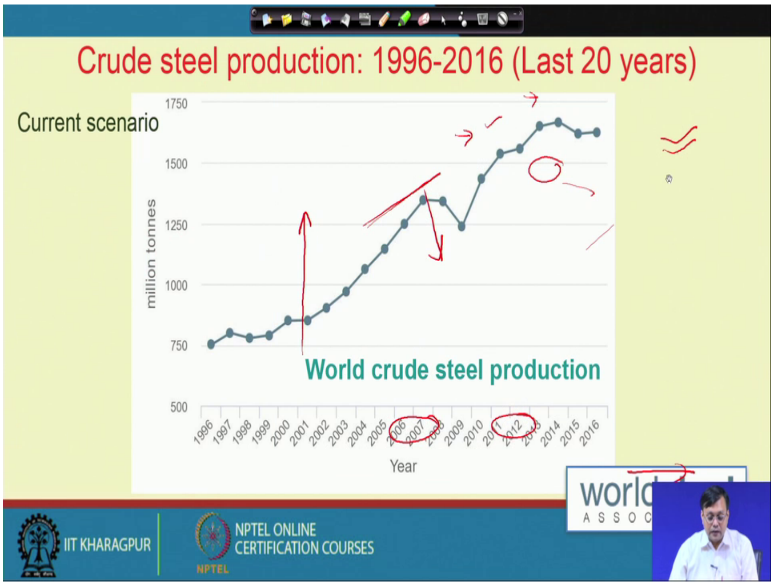

And therefore, we must look at what is the major driving force for let say developing these kind of advanced alloys. Let us have a look at the crude steel production because we believe that the steel production reflect for a developing countries, and its production is quite linked with the economy.

So, here you see these a this is a last 20 years data, I have taken from world steel association and this is the year from 1996 to 2016 and we can we can see that it continuously increases up to something like a 1600 million tonnes.

So, from 750 which was 20 years ago. So, almost 3 times or 2.5 times we have increased as per the world context the whole world context and this is the current scenario and definitely the demand and the production they are quite linked. Because the more the demand, the more the production requires. In that aspect we can also look at some of the developed countries and developing countries and how much they really produce.

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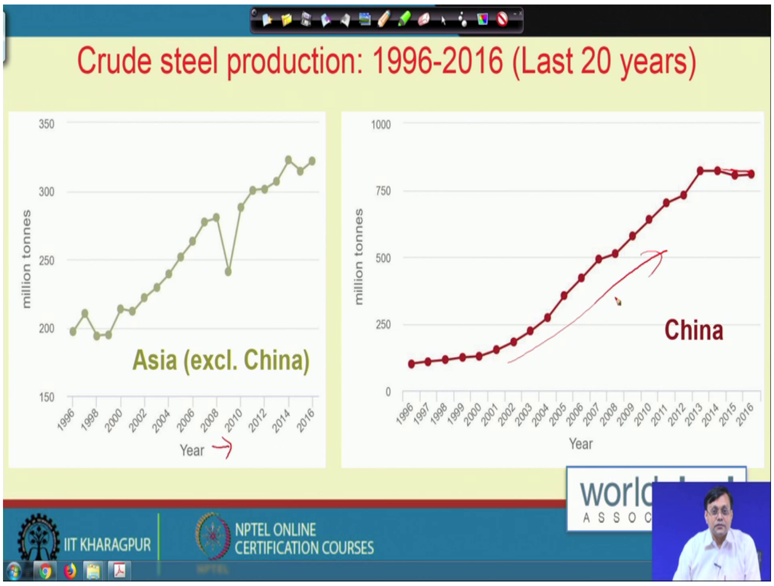

So, as an example, in Asia we can we can see this for the last 20 years from 200 it reaches up to 325 or so on. Asia means including India and so on except China.

In case of China, this value almost something like 100 millions tone, it reaches to almost like 800 or so. This is almost like the 50 percent of the whole world crude steel production. So, that has increase with time a lot. So, these are the developing countries.

On the other hand, if we look at the total crude steel production of the developed countries and they basically show that in case of US, there is a small decrease and also the crude steel production also has decreased a bit. And this is because these advanced alloys are replacing even for some of the conventional engineering alloys. So, this is a just an example that would like to show you.

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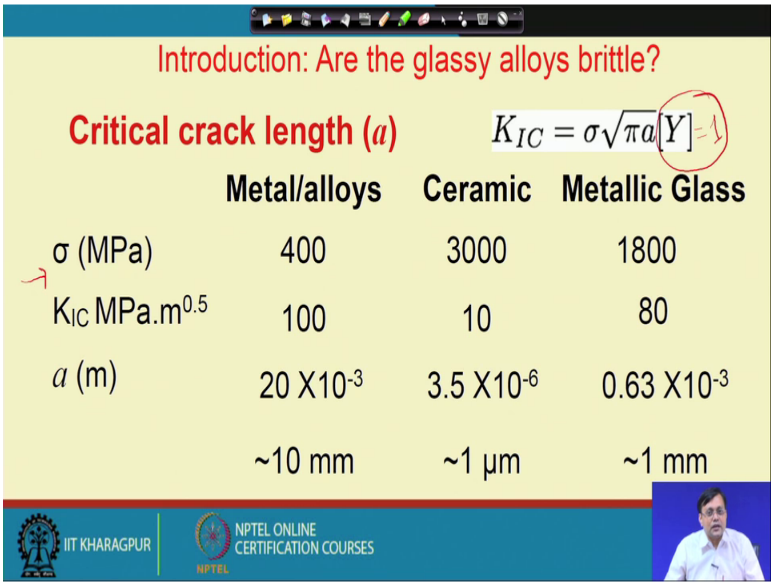

Now, it is a often believe that when we are talking about very high strength alloys, because strength is one of the important properties mechanical properties or let say functional properties also. So, strength is important and we always believe that glassy alloys means probably they are like oxide glasses, that that a material become very brittle because it has very high strength. But if we look at simple Griffith's theory and fracture toughness consideration, then we may conclude that they may not be as we think.

And here I show you a very simple equation, $K_{IC} = \sigma\sqrt{\pi a}$ Y, where K_{IC} is fracture toughness which is linked with the strength σ. 'a' basically means that if we have a crack inside a material and if we simply give some stress then the presence of this crack, which has a length that is 'a' is a length and during application of some stress this crack should grow and they become unstable when the value of K reaches to a critical value.

So, this is the basic definition of the toughness and a so, we can have a look that how all the very common engineering materials like metals and alloys let say like ceramic and let say by comparing metallic glasses, how these values varies. So, let us have an example of the simple yield strength. So, yield strength is somehow in a mega pascal, if we if we if we see the common metals or alloys shows 400 MPa strength.

Now, in case of ceramic, it is something like 3000 because we have a very high strength 3 GPa. Whereas, in case of a metallic glass or bulk metallic glass it is 1800. So, we can see there is a huge variation. So, this values are very close to here ceramic. So, that is why we consider, but if you look at the fracture toughness values of a metal, it is a quite common something like 100 MPa. $m^{0.5}$.

On the other hand in case of ceramic, it is something like 10, 2 to 10 and in case of metallic glass due to metallic bonding this glassy alloys shows something like 80. Now if we consider Y this value of y the value of Y is equal to 1 this value if we consider then we can only put sigma pi and a value and k value in order to get this a. So, here we can have a look. So, lets the critical value of crank crack length so, that is allowable for any kind of engineering design purpose.

So, in case of a metal, it is 10^{-3} m. Now in case of ceramic it is 10^{-6} m, this means it is in the micrometer range like a hair, human hair so, that has a thickness of micrometer. So, hairline crack if we put on a ceramic oxide glass and if we put some stress the material will fail catastrophically; without giving any kind of chance to repair it.

In case of a metal, it is in the range of basically centimeter, we can see this is actually 10^{-3} m whereas, if we take the same in case of a glassy alloys, it is 10^{-3} m. The same order here or let say one order small order little bit less. So, this is something like 1 centimeter, in case of a ceramic it is one micrometer, in case of a metallic glass, we have a one millimeter length scale.

So, a 1 mm crack even there is a presence of such length scale crack in a glass, the material will sustain the load. So, that basically says that the glassy alloys are close to the metallic engineering alloys and not like ceramic oxide glasses. And if we look at some Ashby plots, that will give some more information.

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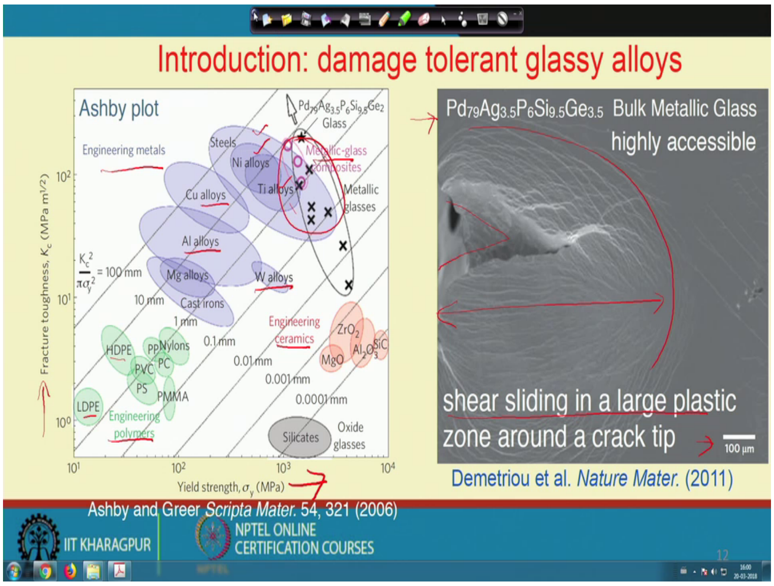

So, here I show you a plot in the left hand side, which is also an Ashby plot taking from recent literature. Please have a look here in the y axis in the y axis, the values of fracture toughness are plotted and in the in the x axis we have yield strength. So, different different or three categories of materials like engineering polymers, engineering ceramics and engineering metals they are occupying very different spaces.

So, one can have a look that the nylons or let say high density polyethylene or low density polyethylene definitely show some lower values of toughness and also lower strength, but important is the steel is occupying at the at the at the top most place here like nickel alloys titanium alloys, copper alloys, aluminum alloys, tungsten alloys and so on. Whereas, metallic glasses are occupying the space almost very close to the conventional titanium nickel or steels.

So, it gives us that there is a high accessibility of metallic glasses or larger process zone size. So, we can use this material for engineering purpose and that is makes them that a very high strength as well as very high toughness. One can see here this is also a recent literature from Demetriou, we can see a shear sliding event a in front of a large plastic zone around a crack tip.

So, thus length scale is almost like millimeter scale. So, the process zone size of let say, a such an example of a palladium base glass is very very high. So, it basically says us that a large number of these advanced high strength alloys could be used, which is also under use and also will be used in future.

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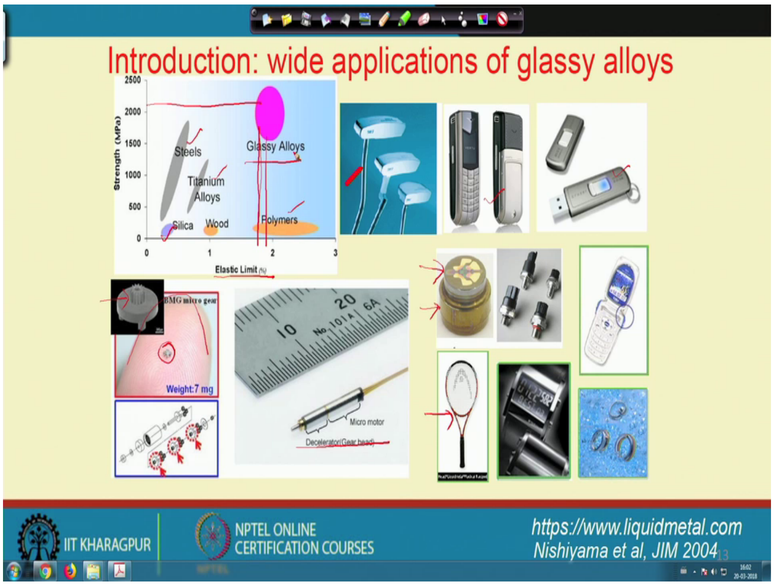

So, people have also explored lot of different application area so far, one can see, these are the golf clubs because of the high elastic strain limit one can one can use them for golf clubs because they have a very high resilience, they can store a very high amount of elastic energy.

So, one can one can use them. Also for very high aesthetic nature and surface finish one can use as a case, like also some of the USB stick a cases and so on. Another important plot is shown here, one can see here that the glassy alloys have a very high strength, at the same time, it has a very high elastic strain limit. So, almost like 2 percent, which is far superior to the conventional steel or titanium alloys or polymers or silicate glasses.

So, this high elastic strain limit one can exploit these material for sensors. This is a simple pressure sensor like a diaphragm is used an often used for different purposes also in this tennis racket and so on.

On the other side of the mechanical properties, this material shows very good soft magnetic properties. A soft magnetic properties means that almost 0 core losses. So, we can take the advantage of the smaller dimension, this is a typical fingertip and this is the dimension of such a small motor that is used for a micro motor a developing some micro motor. So, not only the mechanical properties, but also many other functional properties like magnetic properties and so on this material this glassy alloys cloud be could be used.

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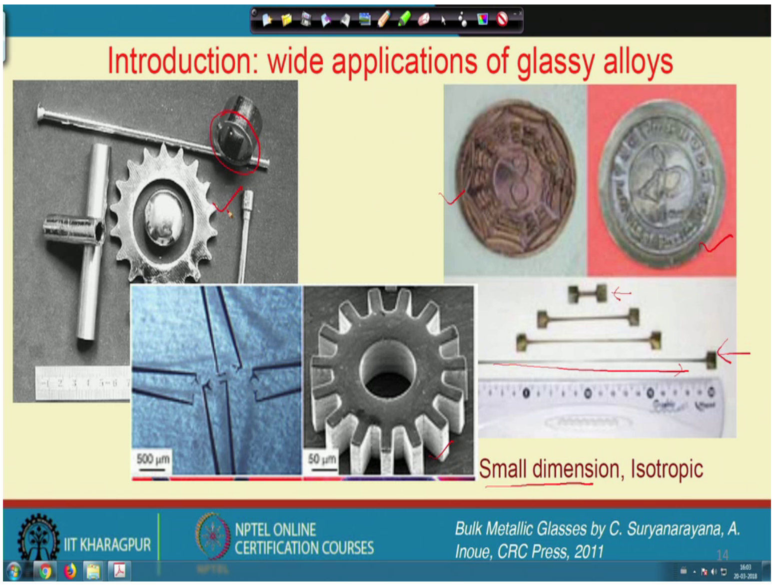

Also, one can see some a bigger image of such small motor and here I show you a micro gear that is used for MEMS that gives you very smaller dimension, but the most important thing that whenever there is a crystal structure then a anisotropic exist in terms of properties.

But since, the atoms are organized randomly in this particular gear. So, we can get all direction the same hardness values. So, hardness and mechanical properties strength and so, on also the processability is also very high, because we can go to the super cool liquid region close to the glass transition temperature and we can extend such alloys and give a some a super plastic like behavior

We can also make a litho and produce a very good dimensional tolerance and a very low wear rate for making any kind of litho or imprint technologies. These kind of hollow pipes can be also produced on a very large scale by these glassy alloys; also large size gears can be produced. And so, it basically says that these alloys may replace some of these conventionally used alloys and there is a large prospect of these advanced alloys or metastable alloys.

Thank you.