Basics of Materials Engineering
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Lecture - 02
Materials Property Landscape

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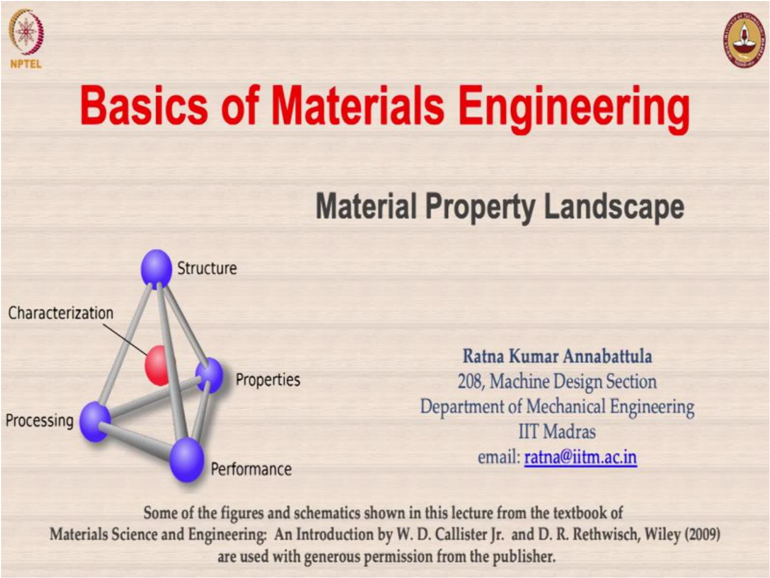

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So far, we have looked at the materials that changed the history. So, we looked at wood, ceramics, fiber and cloth, and so on.

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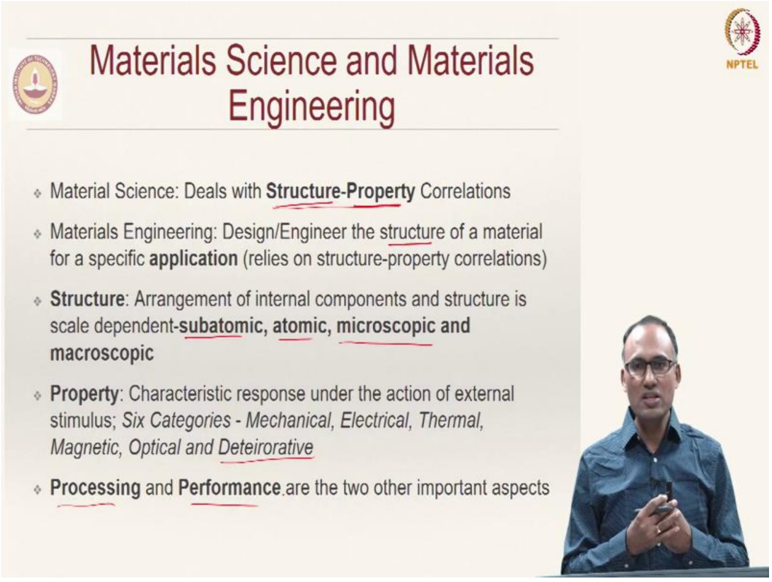

So now, let us look at the concept of what do we mean by material science and what do we mean by materials engineering. Or, in other words, let us see how these two fields of study have been classified.

So, the material science per se actually deals with the structure-property correlations. So, basically, what is the structure and what is the property that is obtained in the material through that structure? So, material science deals with the structure-property correlations, while materials engineering deals with designing or engineering of the structure of a material for specific application.

So, basically it relies on structure-property correlations, and it takes from there, and then tries to design structures or components of a material, for a specific application in mind.

So, what do we mean by structure? A structure is nothing but the arrangement of internal components, and it is actually scale dependent. So, what do we mean by arrangement of internal components? What are the components that we are looking at?

So, depending on the scale at which we are looking at or depending on the resolution at which we are looking at, the structure can be a subatomic structure, wherein we are actually looking at how the electrons, protons and neutrons within an atom are arranged, or at a higher resolution (or higher length scale): what is the structure at atomic scale?

So, that means, how the atoms are arranged in a given material. And later, at much higher length scale, you can have a microscopic structure, wherein how the agglomeration of these atoms as a grain are arranged and then finally, the macroscopic structure, meaning, at the component level, how the structure or system is looking like?

So, whenever we are talking about structure, it is actually a scale dependent phenomenon. That means we should know at which resolution we are looking at, right? So, in order to get the information necessary for us we need to choose the right resolution at which we need to look at, in order to understand the structure at that position.

And when we say property, because the material science as we have said, deals with structure-property correlation. So, we have defined what is structure. But then what do we mean by property? So, property by definition is the characteristic response of any system under the action of some external stimulus. So, if you give an external stimulus to a system then the response, or the characteristic response offered by the system is called the property of the system.

So, what are the different kinds of external stimulus that one can apply? We have primarily categorized them into 6 categories: mechanical, electrical, thermal, magnetic, optical and deteriorative properties, right? So, mechanical means if you apply an external load, electrical means in an electric field applied to a material and how the electrical response of the material looks like.

When you are applying a mechanical load, the deformation behavior is the characteristic property, right? So, for instance elastic modulus is a property of the system, that depends on the interatomic bonding in the material, right? So, you need to know how the interatomic bonding is existing in the particular material, and that gives rise to the property called elastic modulus.

Some other properties might require the information at higher length scale, right? For instance, if you are talking about yield strength, then we are actually talking about dislocation motion that is at a much higher length scale than the individual bonds between the atoms. And similarly, thermal, magnetic, and deteriorative. When we say deteriorative property, we are actually talking about, say for instance corrosion.

So, corrosion is a chemical phenomenon. So, that depends on the environment and the material that we are looking at. Some of the materials in a particular environment might actually corrode faster compared to other materials, right? So, that is also an important property of a material.

And then in addition to the structure and property, which we have already introduced as the main objective of material science, there are two other important aspects to the study of material science and engineering, that is processing and performance. And these two aspects will actually connect this structure and property to give a broader understanding of this material science and engineering.

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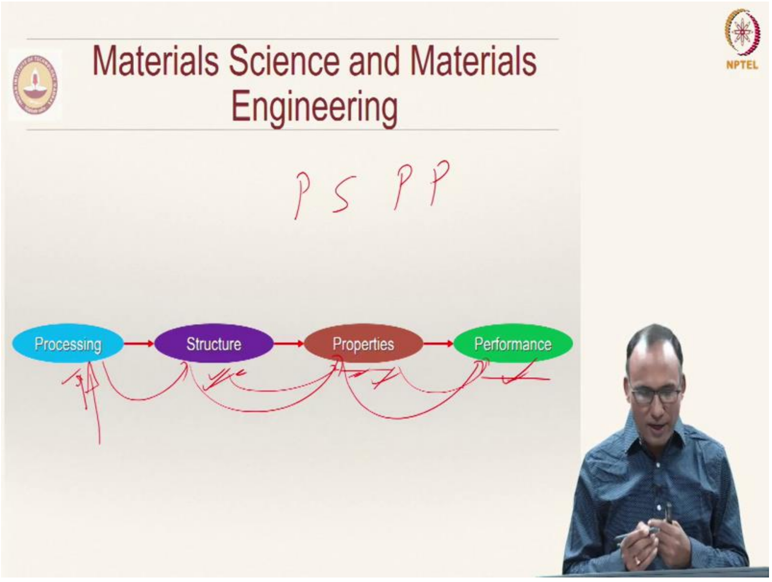

So, this diagram is popularly known as PSPP diagram in material science. Here we see processing, structure, property, performance. So, the way that we should look at this line diagram, is that we know as we have discussed already the properties of a given material depend on the underlying structure.

So, the different properties might depend on structure at different length scales, but there is a clear correlation between the structure and the properties. And once you have a property, and using a material of certain property, you can define what is going to be the performance of a component made of that particular material, right?

So, the performance of a component that we are designing, of a particular material, depends on its properties, right? So, for instance, if you are talking about designing a shaft, and you want to ensure that the shaft does not yield during the operation, that means, that does not plastically deform. So, the yield strength of the material is a property of the material.

For instance, if the shaft is made of steel then, the yield strength of this steel is a property that is going to determine what is the performance. What do we mean by performance here? When we are applying a load, whether the material will yield or not under the applied loading scenario that is prevalent for that particular structure.

So, the properties closely govern how the component that you are going to design out of this material is going to perform. Alright, so, where does processing come into picture? So, we said the structure is what is going to give rise to the properties, but how one would obtain a given structure? So, the processing route that one takes in order to develop a particular material determines the structure that is going to be induced in the material, right? Particularly at the atomic and higher length scales.

So, the processing is the key which will give rise to a structure, and that in turn gives certain properties that will determine the performance of the component, alright?

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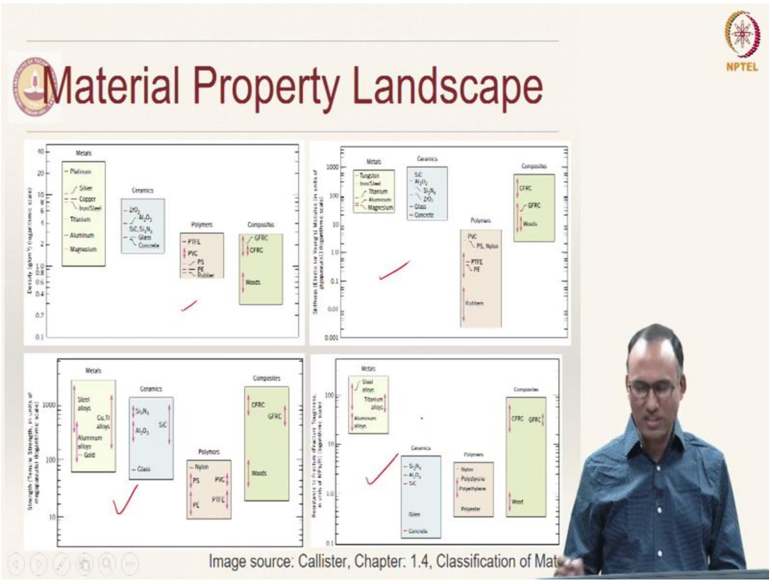

Okay, so, having discussed the fact that the properties are the important aspects of the material which is going to govern the performance of the component, we are going to look at the material property landscape. Here we are looking at four different properties.

However, there are other properties which are of importance in general, but here in this class we are going to look at these four important material properties called density, elastic stiffness, tensile strength, and fracture toughness.

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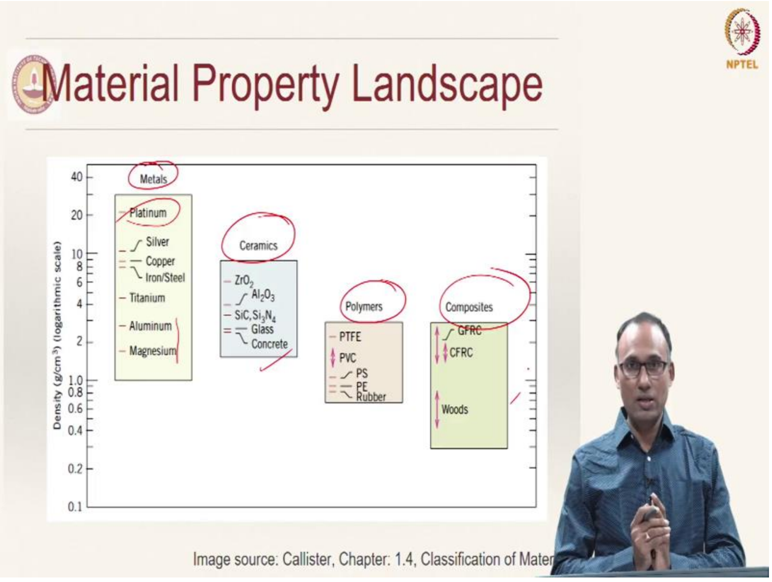

So, let us look at each and every one of them. So, here we are showing density for different class of materials. So, we have four different classes: metals, ceramics, polymers and composites.

So, we see that the metals seem to have a range of density so, that means, different materials. If you are taking materials falling under the class of metals, the metal seem to show a large range of variation of density. There are materials which are extremely light like Aluminum and Magnesium, but extremely heavy like materials like Platinum, Silver, Copper and so on, right?

So, in general the metals show wide range of densities, but they are usually known to be heavy elements. And now, let us look at the ceramics. We will see what ceramics are, in a couple of minutes. So, ceramics actually show the densities which is within the range of these metals, but their highest density is usually lower than the highest density of metals.

So, they are relatively less dense compared to metals. And polymers are known to be light, and composites again can show a large variation again, but the composites will, as you can see here, also show a large range of densities, but still you can have these densities of these composites to be much less than the metals themselves.

So, if you are looking at the design of a particular component, you have to see whether the weight of a component is a primary concern or not. If the weight of a component is a primary concern, then you might want to look at the material property landscape, and then decide which of the materials will be the best candidates for the component that you are going to design.

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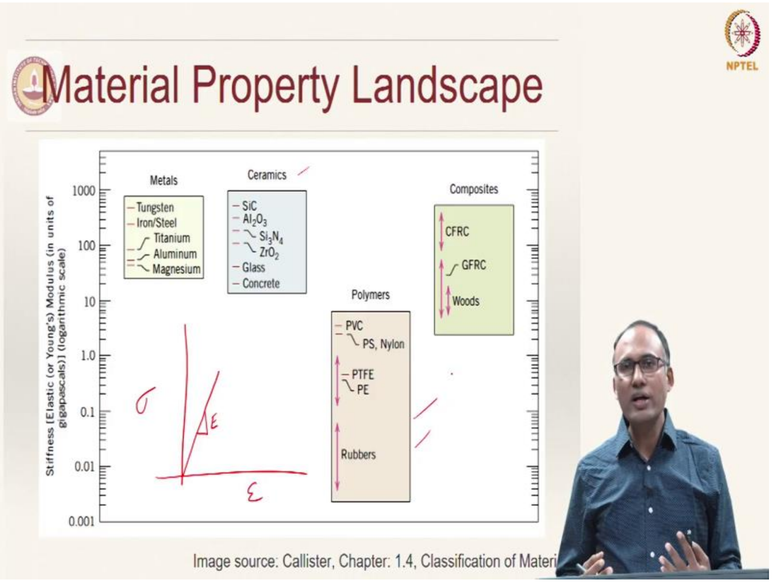

And now, let us look at elastic stiffness. So, basically elastic stiffness is going to give you a measure for the resistance to deformation, right? So, what is this elastic stiffness or Young's modulus of elasticity? If you remember your applied mechanics lab where you have done uniaxial tension test on a material, probably you would have done on steel; then, you would have got the linear elastic part. That is, the slope of this guy is what is called elastic stiffness, and that is what is shown here, right?

So, here you can clearly see that the metals and ceramics show very high stiffness, while polymers show lower stiffness and of course, you can have polymers of different kinds which are spanning from very low stiffness to a moderate stiffness.

So, metals and ceramics are going to show very high stiffness values, while polymers show very low stiffness. That is probably one of the weakest points of polymers. And composites again can show moderate to high values of stiffness.

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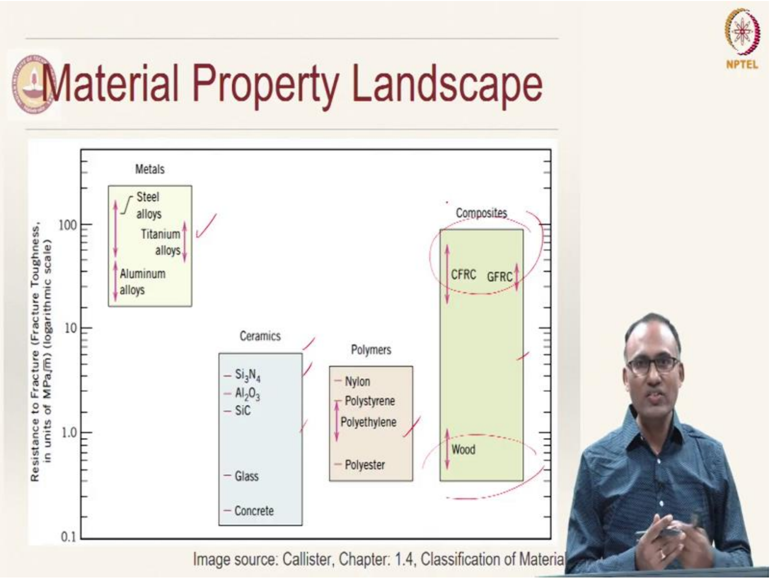

And now, the third property that we are looking at is the fracture toughness. So, the fracture toughness is nothing but is the resistance for the crack propagation, or in other words, the toughness of the material is the ability of the material to absorb energy before actually going to fracture. So, the more amount of energy that it can absorb means that it has more fracture toughness, ok? Again, metals have extremely high fracture toughness compared to ceramics.

Ceramics are not known to be tough, right? They are highly brittle, and hence if they fail, they fail suddenly. Metals will give you some indication that they are actually going to fail. So, ceramics are known to be materials with low fracture toughness, similarly polymers. But again, composites here have again a range. So, they go from very low fracture toughness to almost similar fracture toughness as metals.

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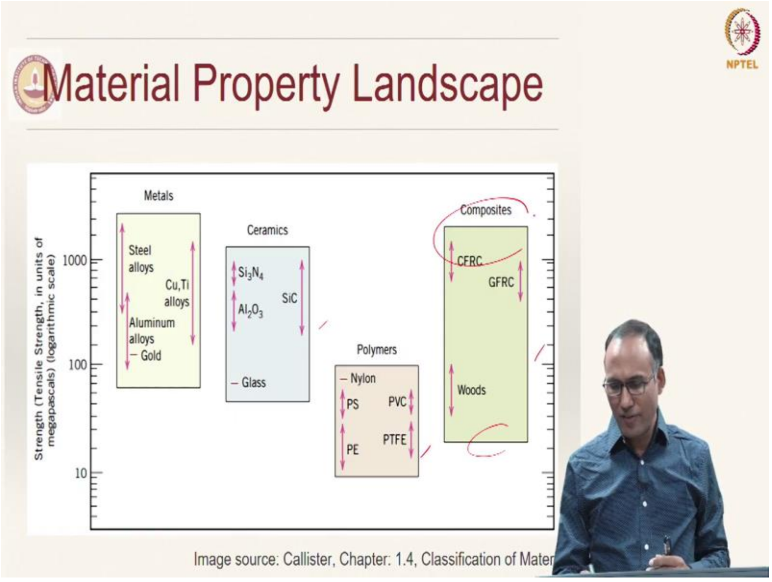

And the last property that we are looking at is tensile Strength. So, tensile strength means basically the ultimate tensile strength of the material that you have probably already measured for steel in your applied mechanics lab.

Here, you can see that the tensile strength of metals again is higher. And ceramics also have similar or sometimes more tensile strength. Polymers again have a low tensile strength and composites again have a range. So, very low value to very high values, right?

So, this is how the different kinds of materials exhibit properties as we have seen here. And by looking at this material property landscape, one can make an informed decision on the choice of the material for a specific application.

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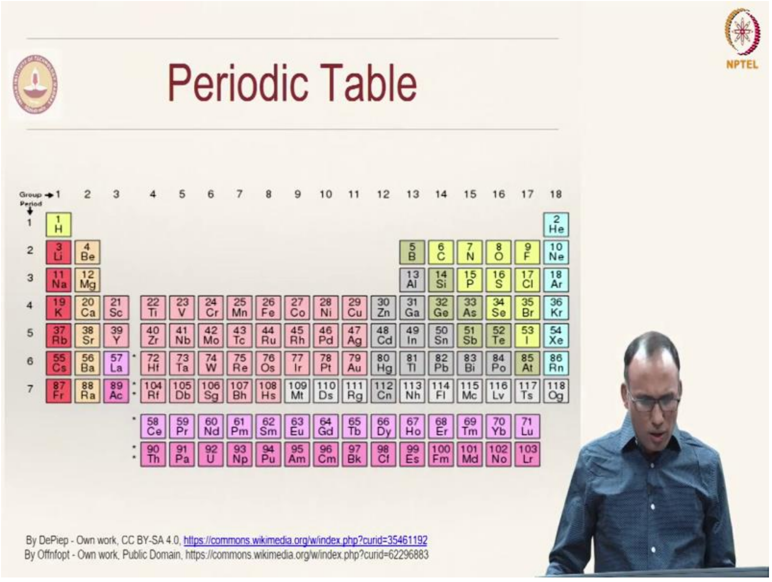

Alright, so you have seen that in the previous graph, the metals, and of course, in this course we will be focusing only on the study of metals in particular. And so, here we can see that metals seem to have all these properties at the higher range, including the density. That is probably one of the downsides of metals because they are heavier, but otherwise they show very good strength, very good stiffness, and very good fracture toughness, alright?

So, if you look at periodic table, let us see how we can classify the elements in terms of metals and nonmetals.

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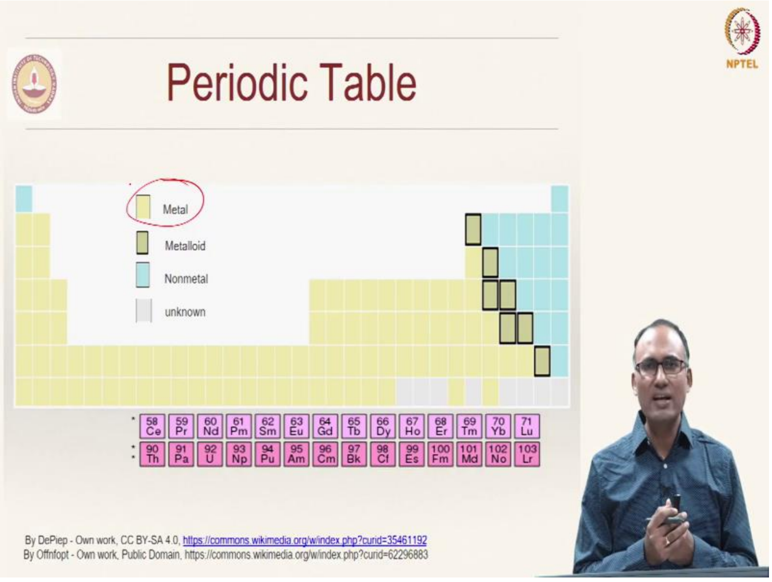

You can see that a large fraction of elements in our periodic table are metals and that is also another reason why it is important. So, that is also another reason why we would actually come across several components made of these metals. And studying the properties of these metals is one of the interesting endeavors, that gives us lot of understanding about the mechanical behavior of materials.

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So, this is the broad classification that we have already seen: metals, ceramics, polymers, and composites.

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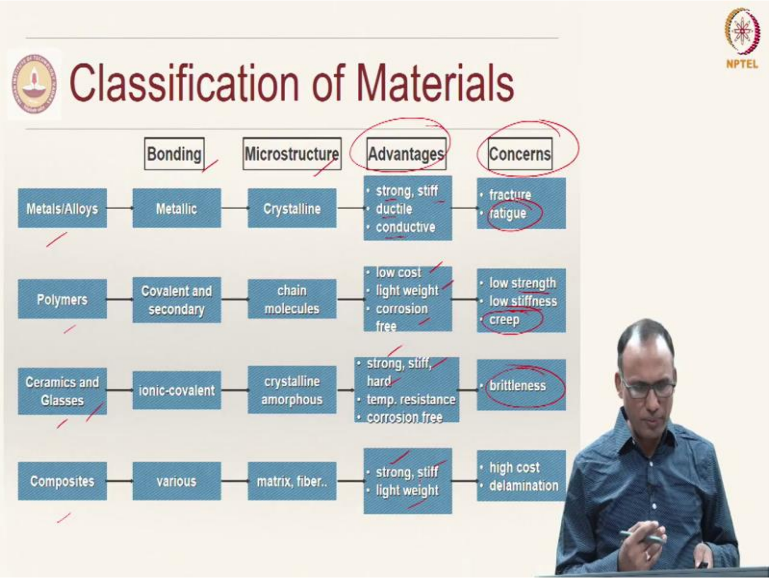

So, depending upon the type of bonding, type of microstructure and the relative advantages and relative concerns of these four classifications: metals, polymers, ceramics, and composites. So, we know most metals are known to be crystalline, or metals and alloys are known to be crystalline, and some of them may be amorphous also.

And they are usually very strong, stiff, ductile, and conductive, but the major concern with them is the fatigue failure of these materials. Similarly, polymers again have advantages: low cost, low weight, and they are corrosion free. Whereas, metals are known to be suffering from the property problem of corrosion. The problem with polymers is they have low strength and low stiffness, and they actually show this behavior: creep failure.

And similarly, ceramics are extremely strong, stiff, hard, and high temperature resistant, but they are extremely brittle. Their fracture toughness is a major concern. And composites, which are a relatively new class of materials, show very good strength, stiffness and lightweight. The only problem with the composites is very high cost, because of their manufacturing process being extremely complicated compared to rest of the materials.

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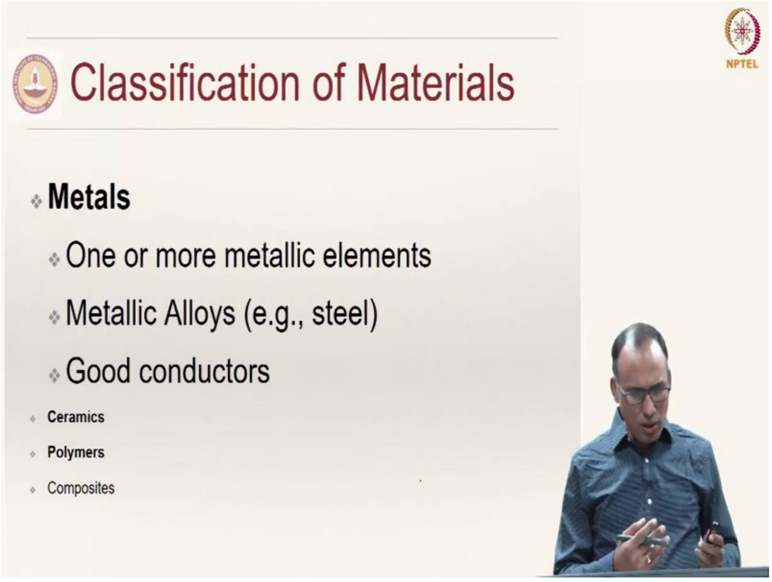

Metals or alloys are usually very good conductors.

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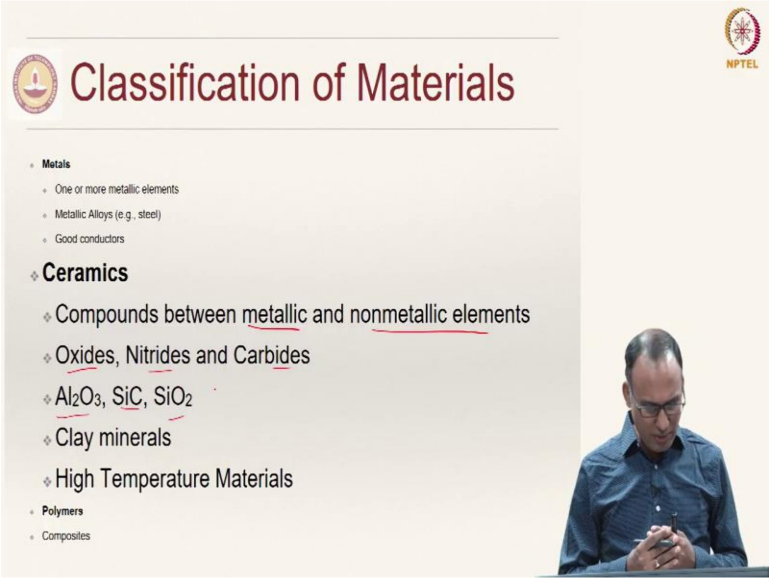

And ceramics, they are actually compounds between a metallic and non-metallic element, and they are known to be in the form of oxides, nitrides and carbides, such as aluminum oxide, silicon carbide, silicon dioxide, and so on. And clay minerals are examples of ceramics, and they are extremely resistant to high temperature.

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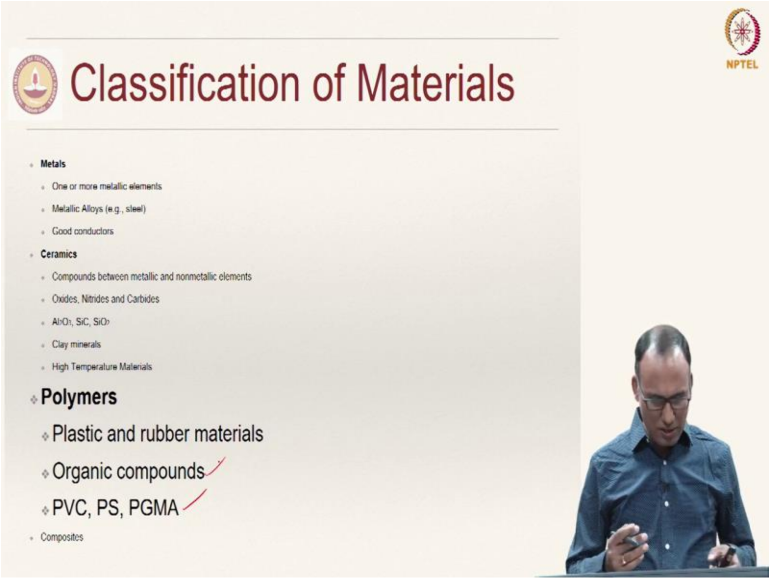

And polymers, such as plastics and rubber, are usually organic compounds, because organic elements like carbon are part of these polymers. And the typical examples are PVC, PS and polystyrene, poly glycidyl methacrylate.

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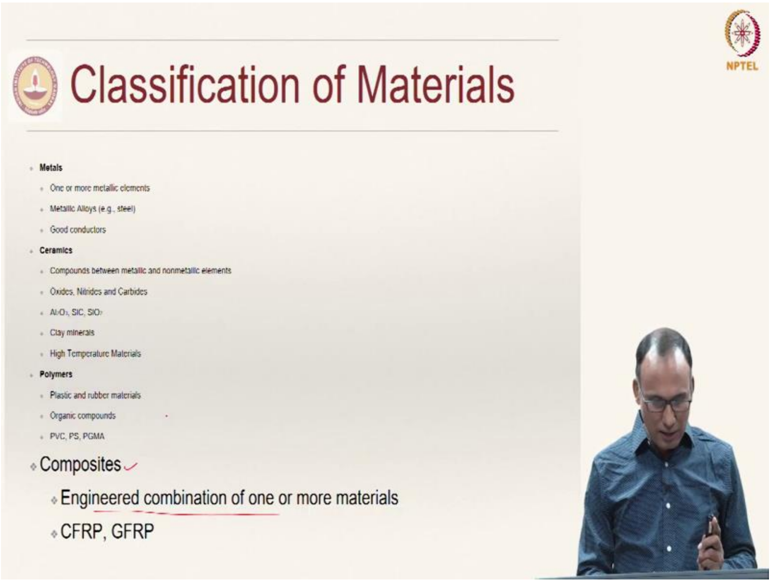

And again, composites are a recent class of materials which are basically an engineered combination of one or more materials, right? Carbon fiber reinforced plastic composites and GFRP. These are all different kinds of composite materials which give unprecedented material properties, which were not possible before and which could not have been achieved before unless until the composites came into existence.

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And there are advanced class of materials. Now, people are looking at semiconductors which we have already been using extensively in all the electronic equipment. Now, people are talking about biomaterials. So, for instance, bio implants and tissue regeneration materials and so on.

And smart materials, suppose, if you take a material and if you give an electric field then it will give you a mechanical response. So, that means, depending upon the surrounding environment, the material can respond to the stimulus provided by the environment. Such materials are called smart materials.

Another very important class of materials called nanomaterials, which are actually a special class of materials in which certain components are having sizes at the nanometer scale, that gives rise to unprecedented properties for these materials and which make them one of the most attractive class of materials for modern applications.

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Alright, so, with this information, we will start digging deep into the world of materials and try to understand their properties. So, here we have shown, say, for instance, different mechanical components like gears and gear-hub and so on. And, if you zoom a little bit into that you will have the microstructure.

So, here you can see individual grains. Here, the scale is 10 microns. And if you further zoom into it, then you will see dislocations. So, you can see the dislocation structure and further zoom into it, one can actually see the individual atoms. So, the performance of these materials is going to depend on several features at these different length scales. And those features are going to govern the properties that are going to be imparted into these materials which in turn govern the performance of these materials.

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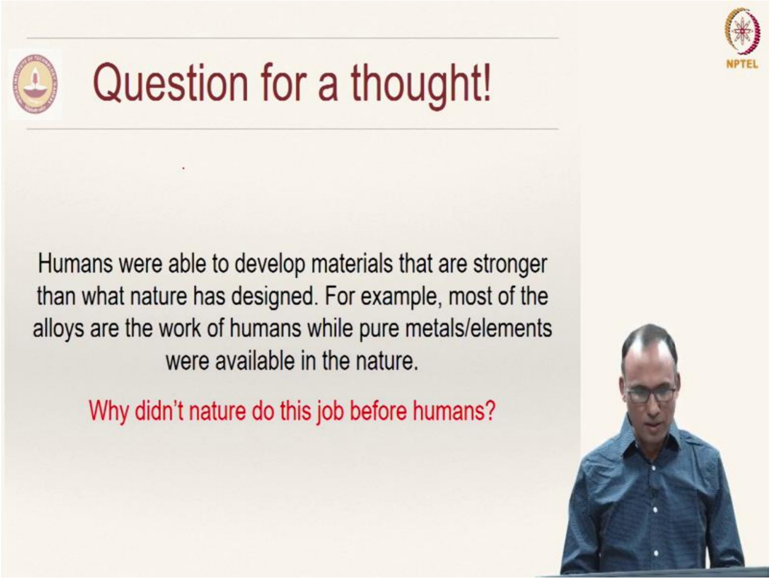

Ok, so, before we close this session, one question for thought. So, humans were able to develop materials that are stronger than what nature could design, right? For instance, nature has a metal like iron, but it never made steel. Steel is something that humans have come up with, right? So, for example, most of the alloys are the work of humans while pure metals or elements were available already in the nature.

So, if humans could do it, why did not nature do this job of making stronger elements, stronger materials, or alloys that humans could make? Think about it and try to find an answer. And we hope to find this answer for this question probably during this course.

So, with that, thank you for your attention.