An Introduction to Materials: Nature and Properties (Part 1: Structure of Materials)

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Lecture - 01
Materials Evolution

So, we will start this new course on nature and properties of materials and we will start the first module of this particular course that is based on a structure of materials. So, I am Ashish Garg, I am a professor at the department of material science and engineering at IIT Kanpur and following my contact details in case anybody needs to contact me. So, as the course outline has mentioned, that this course is useful for UG and PG students of nearly all backgrounds even those studying materials in metallurgical engineering can do that.

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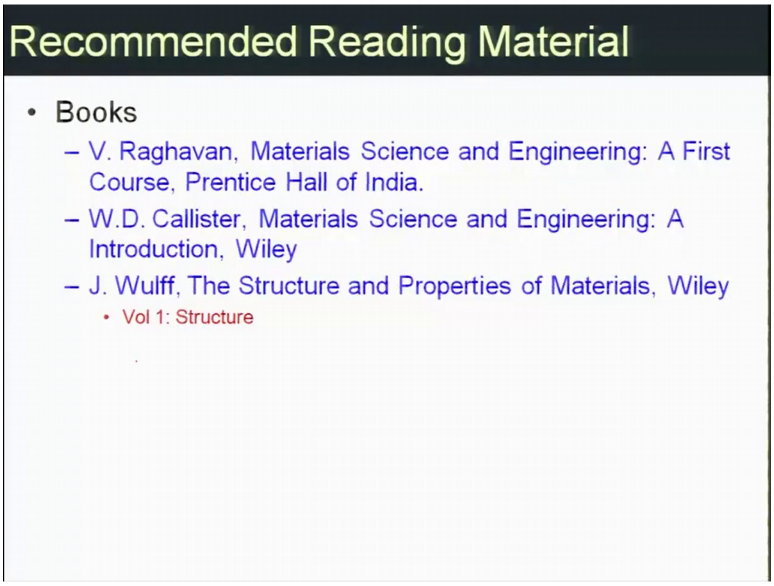

So, the recommended reading material for the course is I have listed three books here, first is the book by Professor V Raghavan which is Material Science Engineering a first course which has nearly all the elements of Material Science and Engineering at least the basics if not in detail and then second good book is by Callister which is material science engineering.

Again its introductory book and third book is actually a four volume set by John Wulff structure and properties of materials by Wiley it is a very old book perhaps not available very frequently it has, but the first volume is related to the structure of materials. So, it is a very good book, if somebody wants to get into a little bit of details. So, let us see why you know all of us know that materials are very important our civilizations are named after materials, and in the development of humankind materials have played a very important role and that is why we have ages like Bronze age, Stone age you know Iron age and so on and so forth and currently we have silicon age or electronics age.

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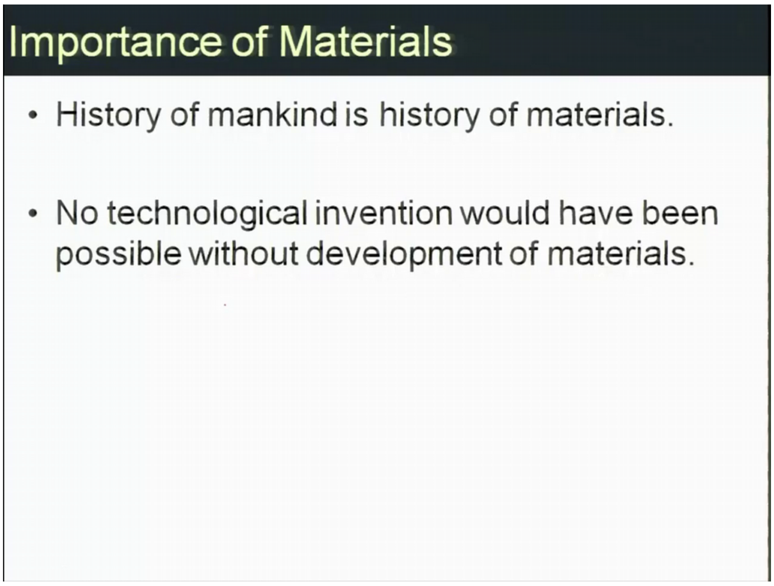

So, as we know materials are very important, they have been important throughout the history of mankind is basically you can say is steel of materials and if you if you go back to our ancestors, they were earlier using stones and then they started inventing materials and strangely precious metals came before many of the materials and followed by development of copper based alloys which bronzes various bronzes, if you if you go back to Indus Valley Civilization, you see lot of bronzes and grasses and then of course, invent advent of iron gave rise to substantial advantages to the human beings.

Because iron was a stronger material, it could be it could be used not only in warfare, but lot of other practical things. It made the hunting easier as compared to stones and other objects. So, and if you go back to if you come if you come closer to our times, since past 200 years or. So, the advent of electronics or electricity has led to materials based on let us say electronic age silicon based materials because of which we are utilizing all the devices which are basically silicon based.

So, as we stand now perhaps more technological invention would have been possible like all the gadgets that we have, all the technologies that we have, all the healthcare devices we have, all the automotive devices that we have, they probably would not have been possible without concurrent development of materials. So, materials in that sense are very important for us and that is why it is important to study the science and engineering of materials.

So, in this course we will it is a introductory course, we will talk about the basics of materials which will help you to advance further in this discipline.

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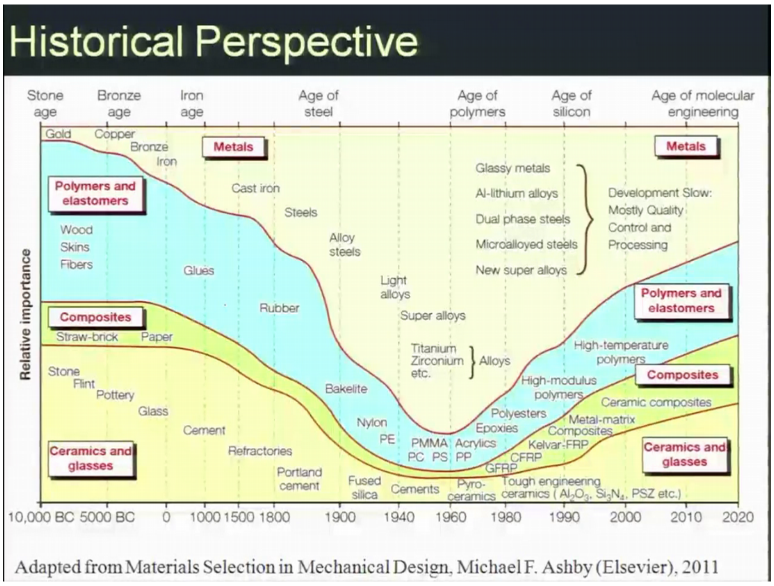

So, if you got the historical perspective you know going back to 10,000 BC man was using things like stone, straw break, wood skins in fact, strangely in, gold came quite early. And then after 5000 BC or so, a man started developing potteries which are based on ceramics and glasses composites was used in paper for example, polymers in elastomers were used in wood you can say wood is example of polymer.

And then Copper, Bronze Iron they came before 0 AD in Indus Valley Civilization in various other civilizations. And then comes the iron age which expands the use of metals because of advent of iron and then at the same time and also kept using things like ceramics and glasses in the form of cement factories, because they needed to build houses and mansions and palaces and so on and so forth.

And as you keep moving down the down 1900s, you can see that iron gave way to cast iron followed by steels steel was far better material as compared to iron alone, and then development of alloy steels which in fact, improved the steel. So, this is basically age of steel as one can see. Now steel was very good, but man invented you other materials which are even lighter and stronger. So, that is where things like aluminium alloys, titanium alloys, zirconium alloys, all those came into being which are lighter and stronger, and super alloy which would work at high temperatures.

And then after you can see that 1960s or so, this curve start going upwards which means metals are slowly shrinking in their domain, and there are other materials which start expanding. For example, new ceramics come into picture earlier we were limited to a stone you know glass, cement, refractory etcetera 60s gave rise to pyro ceramics; which means which ceramics which could be used at high temperatures, toughened ceramics and their importance has increased over period of time. And men also started developing lot of synthetic polymers and these synthetic polymers give rise to array of applications, which are basically polymer based because polymer is a light material.

And then composites also by mixing stone and by mixing ceramics and polymers or metals and polymers and metals and ceramics, man made these composites which have which had properties which are different to which are which are compromise or both let us say metal and ceramic. So, it is a bit of a mix of both of them. So, you can see that the arena of materials has changed dramatically as a function of time, and today a 1990s for example, somewhere around 1950s let us say advent and the vacuum technology processing technologies, give to the manufacturing of silicon.

So, today we stand in the age of silicon and perhaps today is the age of molecular engineering as well, because we are looking at materials and using materials at the molecular scale a very very thin films 2D structures such as grapheme and (Refer Time: 07:02) side spectra are being used are being studied at least if not used. So, we can say that we are study we are standing on had a completely different era of materials, which is very different from what we had earlier.

But nevertheless the message is we would know if we would not have reached where we are today if it was not for the materials that we invented over our course of development. So, if we classify these materials which are basically most of the engineering applications, there are few categories in which we can classify. So, first one of course that comes to our mind is metals and alloys.

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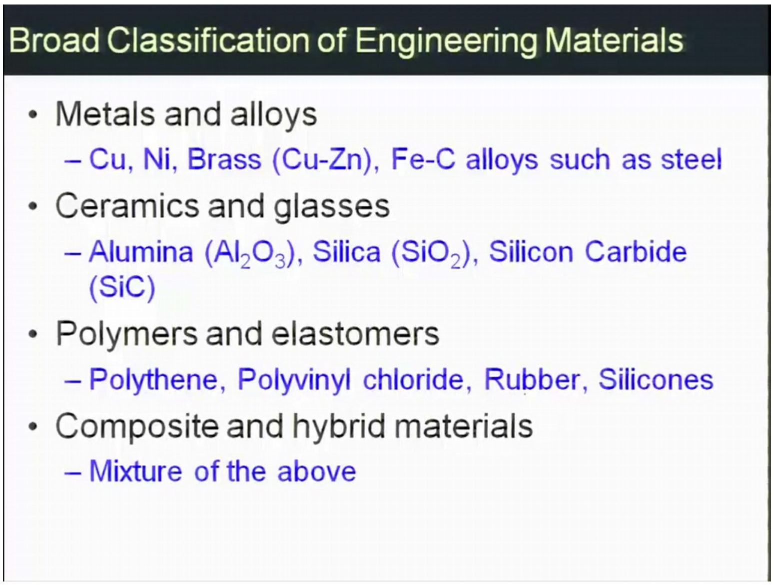

Metals and alloys; so, copper is for example, a metal, nickel, brass, which is alloy of copper and zinc, you can have iron carbon alloy which are nothing, but steel and cast irons. So, anything copper and nickel, brass, bronze iron, iron alloys zirconium, titanium, aluminum, all of them are metals and you can make alloys of them by mixing them with various elements and they have very good properties. Metals typically are very ductile they are also a reasonably strong and they can be used in applications starting from low temperature to high temperature.

So, and they are ductile you can you can make them very easily. So, these are some characteristics and they are also electrically and thermally conducting, that is why metals are used extensively in our in our world. Second category of materials ceramics and glasses ceramics examples are for example, aluminum oxide, silicon oxide, silicon carbide, magnesium oxide, titanium oxide all these oxides, nitrides, carbides basically happen to be ceramics and they are different from metals, because they have they are much more brittle they have but a very strong, they have high strength or you can say high modulus, but they are also a brittle they cannot absorb the shock.

So, if you if you if you subject them to impact loading, if you are drinking if you drink tea in a glass cup you know that if it breaks it shatters whereas, metal does not do that. So, which means its brittle, but there are certain applications in which ceramics are important because ceramics a high temperature materials and they also have low coefficient thermal expansion. So, things like refractories, bricks and kilns ceramics a very important cutting tool, they also have high hardness so, they could be very important there.

Metals on the other hand are typically used as structural materials as bridges, houses, rods, automobiles anything which is which has to be strong ductile yet ductile and tough you use a metal depending upon the temperature and strength that you require.

Third category which is if you if you go beyond wood and natural polymers is the polymers in the last tumors, which are very light material they have low elastic modulus, but they are very flexible and you can make extremely thin structures very light structures out of them, they mostly contain light elements like carbon, nitrogen, oxygen, etcetera.

So, examples could be polyethylene which is used just like a plastic bag that we use on daily basis, PVC I mean you must have heard of PVC, PVC is polyvinyl chloride, which is used for ducting you know piping and all that it is a strong material, but its light it does not corrode there another advantage of polymers is that they do not corrode. So, metals for example, if you make a metal pipe and your savage flush goes through them they corrode, but polymers do not corrode.

So, their light they are easy to make they do not corrode, they cost less you have another example is rubber used in tires and all that, silicones lot of silicones is used in variety of applications these polymers in elastomers are another class of materials which are very different to metals and ceramics in the sense that, they are not so strong, but they have a light they are way and they have high flexibility and they are very tough they could be very tough and you can make things from them rather easily without going to high temperature processing of metals and ceramics.

So, polymers have made our life easier, I mean plastic bag for example, has made our life easier, because things do not go bad and then fourth class of the materials is called as composite hydra hybrid materials, which is basically a mixture of the above. So, you can mix a metal and a ceramic make a metal matrix composite. So, you utilize the properties of both metals and ceramics. Similarly you can make a polymer matrix composite you mix polymer and ceramics together. So, you use the advantage of polymer as well as ceramic. And you can mix polymer in metal as well.

So, basically a combination of the two or three classes of these materials different materials will give you composites, and they have their own advantages. For example, tennis rackets now that we have today is basically a composites or many of the parts and the automotive applications or aircraft applications wherever you require high specific strength or high specific modulus, you predominately tend to use polymers composites.

Because composites have high strength per unit weight, similarly they have high modulus per unit weight and that is what is useful in certain applications. So, these are some of the applications you can see, you see this Plier for holding things is you can see the head of this is made of metal, it is made of metal, because it has to be strong, it should not be brittle, but it should it should provide you a good grip, it should not yield.

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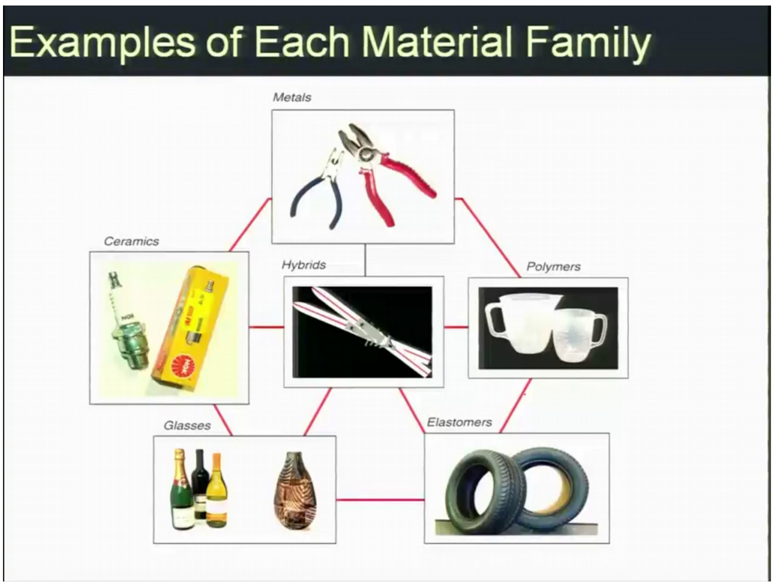

So, it is made of steel typically, but there are lot of other applications of metals you use them for making bridges, they are they are used as a construction material, your cars are a lot of parts and cars are made of metals, steel, aluminum, copper.

Ceramics you can see that ceramic piece here white piece this is basically insulator ceramics is the insulator. So, it insulates the parts of let us say spark plug, ceramics is or ceramics also thermal and electrical insulators. So, they also provide insulation from common electrical. So, for example, on electrical poles you see white ceramic pieces they are nothing, but ceramic insulators. Polymers you can see that these are the applications of polymers, you can we can make mugs, you can make plastic bags, you can make pipes etcetera lot of medical devices are made of polymers.

Elastomers for example, rubber; this is a rubber tire. So, polymers elastomers are sometimes put in same class sometimes they are put in different clubs because of various reasons, we will explain later and then you have another part of ceramics is glasses, and glasses are typically transparent. So, you can make them you can you can make bottles out of them pottery class where whatever the applications are lenses are all made of classes, and something in between you can see is the hybrid for example, this is a ski base tennis rackets, airline, aircraft components, automotive components they are all made of by mixing these materials to make them light yet strong ok.

So, let us see if we go to the next slide.

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So, these are certain applications as I explained to you before. So, ceramics have and just to summarize they have high stiffness, they have high elastic modulus they are hard they have high abrasion resistance, they have a height good high temperature strength, which means they hold their strength up to higher temperatures; higher temperatures typically will mean will mean above thousand degree centigrade. They have reasonably good corrosion resistance, but they are brittle this is a major problem in ceramics.

Because they cannot absorb any shock. So, glasses on the other hand are hard, they are corrosion resistant, they are electrically insulating, they are transparent. So, these are some good attributes of glasses, very similar to what you have in ceramics, but they are also brittle. So, this is again a problem with glass polymers.

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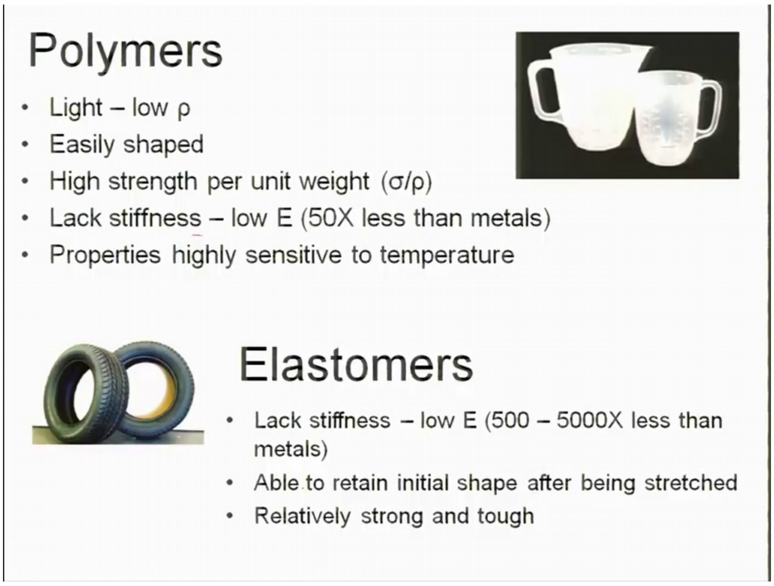

Polymers have low density they are light because they are made of light elements like carbon nitrogen oxygen and so on and so forth.

Hydrogen they can be easily shaped by processes like molding etcetera, they have high strength per unit weight. So, as such their strength is not very high, but if you look at in the perspective of density they are very strong. They lack stiffness which means they have low elastic modulus, but they are very flexible, they can you can have you in good you can make plastic works large strains. So, they can they can withstand large strains.

But their properties are highly sensitive to temperature; because they softened with temperature their melting points are lower. So, plastics are typically not used for applications, wherever you have to subject a material to high temperature. So, plastics are typically suitable for temperatures lower than 1500 degree centigrade, 50 or 100 degrees centigrade depending upon the type of polymer. Elastomer a cousin of polymers, it again lacks stiffness it has low modulus several times lower than metals basically rubber, it has this wonderful ability to retain its shape after being stretched, yeah and you can provide very large strains to a rubber or the last tumor.

And they are relatively strong and tough as compared to polymer and they are used for things like you know these tires and all that. So, similar kind of applications wherever you require a stronger polymer, you use elastomer. But one thing one difference between polymer and elastomer is polymers can be melted and reused elastomer cannot be melted if you melt them the decomposed it ok. So, typically a elastomer decomposes whereas, polymer does not decompose.

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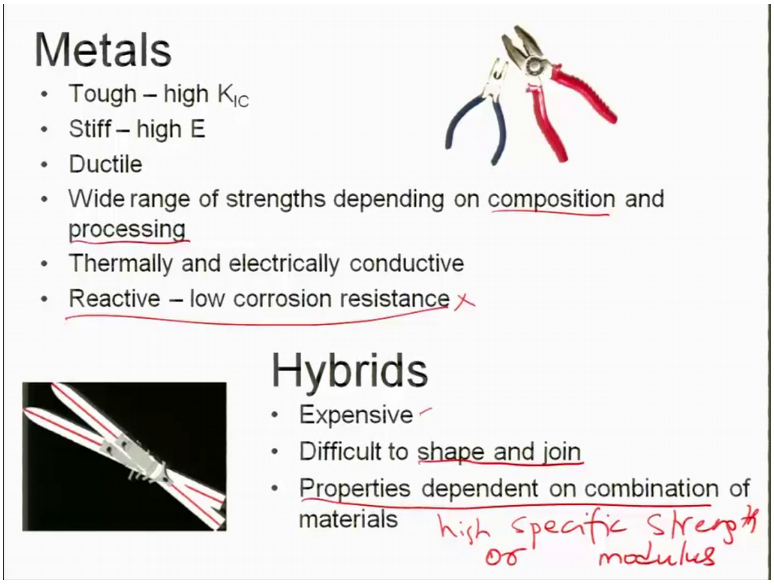

And then we come to metals and hybrids, metals they are very tough they have high fracture toughness this is a parameter called as K I C which is a representative of fracture toughness, we will probably see later in some other course, they have high stiffness, they have high drastic modulus, they are very ductile depending upon the composition processing, what is what is the metal made or whether its iron based, aluminum based, copper based or nickel based they can give you strength which are highly varying you can you can achieve strength from 50 mega Pascal to 1000 mega Pascal even higher depending upon the composition and processing.

So, it is very good to have a metal because you can engineer its property depending upon what you want. Depending on and which can be varied by changing the composition and processing conditions. They are typically thermally and electrically conductive, that is why they are used in applications wherever you require high electrical conductivity and high thermal conductivity; however, most metals are reactive they tend to oxidize or they tend to react with environment and that is why most metals have low corrosion resistance.

So, wherever that atmosphere is aggressive in nature you have a sets, or you have alkaline environment or you have sludges seavers, you cannot make them out of metal because they will corrode as a function of time. So, this is this is a drawback of metal ok. And then we have hybrids, another thing about metals is metals are typically heavy. With the exception of aluminum titanium most metals tend to be heavy. Iron has a density of about 8 gold is very heavy, silver is also heavy, nickel is heavy all of these metals tend to be heavy. Most of the engineering metals I am talking about I mean there are some other metals which we light and they are not very useful.

So, most of the engineering metals with the exception of copper and aluminum and titanium and magnesium they tend to be heavier and metals are typically made by melting root once you made them. And then we have hybrids, which are tend to be expensive because you have to process them in a specific manner by mixing different classes of materials. Since you use different materials they are not very easy to shape and join because metals have different joining characteristics ceramics, have different joining characteristics, polymers have different joining characteristics and they all are process the different temperatures as a result its very difficult to make a good shape out of polymer out of composite and to join them.

So, processing is a little difficult in case of hybrids ; however, you can achieve very good properties dependent upon the combination of materials. So, if you want for example, tennis racket what is what is that you require intense? A it should be light, it should be strong and it should not yield ok. It should it should have it should it should have a. So, when the tennis racket hits, it should flex a little bit it should be able to flex a little bit without deforming permanently or breaking. So, that is achieved by making a composite which is let us say carbon composites of polymer carbon composite.

So, depending upon what you mix and how you mix and what kind of shape and size of materials are, you can tailor their properties extensively. So, they typically give you high specific strength or modulus, which are required basically in automotive and aircraft applications. So, these are certain examples of materials.

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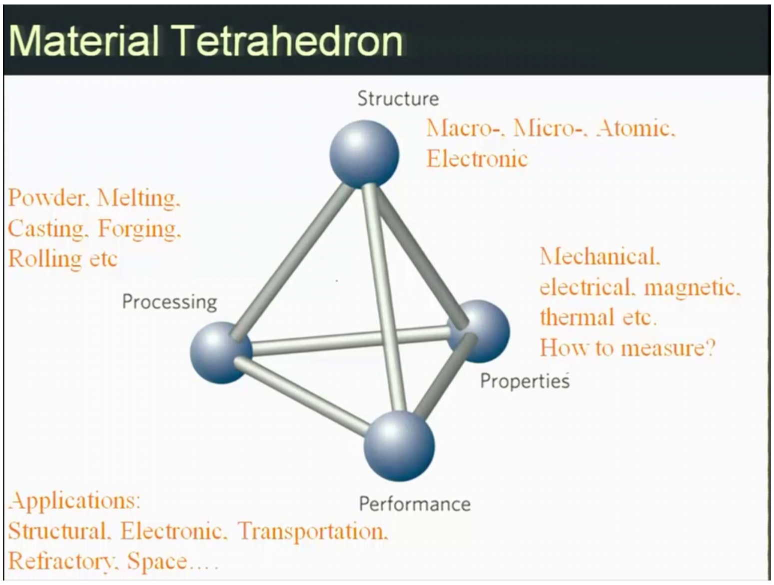

So, now let us look at what is that which makes materials important or how can you engineer them. So, this is called as materials tetrahedron which consists of four parts, one is the structure of materials and this is what this? This particular lecture series is all about structure, but a structure is a very wide connotation there are various meanings of structure. So, structure for example, could be I will tell you a little later. So, a structure is one thing, second is properties, properties could be mechanical property, thermal property, electronic property, optical property various properties.

Third is processing, how do you make a material, how do you process a material to bring it to a particular shape and size that you want and then performance. Performance is related to the applications that you are looking for example, what is the application. So, if I go a little further. So, applications for example, could be structural application like bridges, electronic applications like the gadgets that you are carrying let us say the mobile phone or display or led or transportation, which could be train or car refractory applications like furnaces or a space application, you know we are sending spaceships to the space.

So, they use variety of materials, which have very different properties and different functionality. So, how do you make them? There are various methods by which you can make materials, you can make you can do powder processing, you can start from a powder and then make a particular component or you can start by melting root, which has to be then casted. After casting you may provide some more mechanical treatment like you can force them or you can roll them, depending upon the material and what do you want to do with that, there are variety of processing methods that are available.

And then we have properties which are mechanical, which could be mechanical property, electrical property, magnetic property, thermal property. So, question is how to measure or how to tailor them. And then we have structure at the end structure of a material is looked at various scale one is the macro structure. Macro structure just like looking at tree if you cut a tree you see something with the naked eye that is macro structure; something if you want to look at it in a little bit more details as to see how different layers are is there any porosity, is there any crack, which is not visible with the naked eye, you look at the micro structure then you go into the microscope.

And if you are not happy with looking at the micro structure if you want to understand the structure even better, then you have to go to atomic structure which means you really have to go to very very fine techniques and then you have to do some modeling as well and if you want to understand even the atomic structure that the properties, which are emanated in a material then you look at the electronic structure.

Electronic structure is typically a modeling based exercise so, a structure of a material depends upon the length scale what you are talking about it could be macro structure, it could be micro structure, it could be atomic structure, electronic structure. So, you can see that length scales decrease as you go from macro to micro to atomic to electronic. And it is the combination of these four attributes or materials, structure, processing, performance and properties which determine the potential of a material.

So, for a given application you need to optimize the properties and you need to optimize the process, process has to be simple, cheap and easy to make. Properties should be according to the application and properties are affected by structure, structure is affected by processing. All of these things are connected to each other and that is why its called its very important to understand this materials that are heating.

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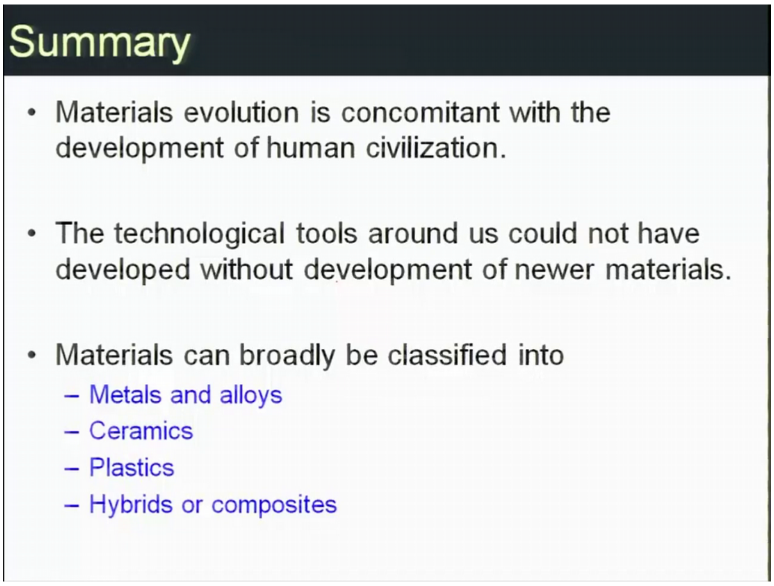

If you have any questions in between you can. So, this is basically early summary of the content that we are talking about, materials evolution as we saw is concomitant or in synchronous with that development of humans, we could not probably have developed any other technologies that we use today without the meant of materials successive development of new and new materials. Today with the understanding of science, physics and chemistry, we are able to classify these materials into various classes metals and alloys, ceramics, plastics polymers and elastomers in that category and hybrids or composites.

Now, the question that arises is, what is the difference between these four? Why should we categorize these in materials in these four categories. I mean I showed you the a very basic reason is because of properties, but there is something more fundamental other than the properties there only. And that origin of these lies basically in the bonding of these materials how they are bonded ok.

So, what I will do is that, I will just give you a brief introduction to the bonding of materials before we look into the structure of materials, because bonding is what determines the structure of these materials ok.

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So, before we move on to the discussion on bonding, I will just show you how the structure of materials is important. So, this is the structure of materials at various length scales. So, if you look at a tree for example, this is the cross section of a tree you can see these rings in the in the bark of a tree.

So, this is something which is visible with the naked eye. So, this is called as a macro structure, which means the length scales which are beyond the resolution of I. So, anything which is more than. So, I can resolve for example, a hair a hair is a few microns in size. So, anything which is bigger than that is basically a micro macro structure something which you can resolve with your own eye. If you want to look at into details of this, then you need to magnify it.

So, then you put this material into a microscope, that microscope could be a optical microscope it could be a scanning electron microscope, which can help you resolve things down to microns and few hundred nanometers. So, this is where you see for example, these are the fibers or pores aligned inside a certain fashion, which is not visible by naked eye because a length scale here. So, this length scale here could here this could be a few microns or submicron. This is not resolvable by eye and then you need to put it and put it in. So, so less than let us say a few hundreds of micrometer, you will call it macro.

Micro would be few these are very low definitions not very specific efficient few nanometers to few microns this would be micro structure. So, this is basically naked eye, this is optical or scanning electron microscope and then we have third category. If you really want to go to higher level of details, and then you can look at the structure for material at more at nano scope or lets same atomic level.

So, here this is a transmission electron microscope image of a material, you can see that you are able to resolve things down to 0.5 nanometer, that scale bar you can see is about 10 nanometers. So, so you are able to resolve things down to one half of one nanometer. So, this is called as nano or atomic structure by proper careful imaging you can also try to look down the atomic arrangement in a material. And if you want to understand this even better then you need to do what we call as a comic simulations, which tell you about the atomic structure of the materials.

Now these are basically atomic structures, which can which further go to atomic slash let us say electronic and these are. So, this is basically done by tem. So, this lets say is less than a micron. One micron and typically up to down to about a half a nanometer and if you want to go down that below this, you cannot do microscopy you need to do simulations. So, this is by simulations or modeling.

So, these are the four levels of structures, which are present in a material and it is very important to understand these structures because how they how the structures are made what is the distribution of various things, what is the size of various things, what is their morphology, how they are oriented and various other things, they will determine what the properties of a material are, and what the and those properties will determine the applicability for a particular application and this structure is controlled by basically the processing.

So, that is why I showed you the tetrahedron which is very important. So, in the in the next lecture we will now we will talk about we first talk about the bonding of materials just to have a bit of idea about what the bonding is and how about how that particular bonding is related to the classification of materials that we did, and then we will move on to the. So, in terms of studying the structures, we will start from the smallest scale first and then go to the largest scale later on so.

Thank you.