Welcome to the third lecture in the course Physics of Functional Materials and Devices. In the first two classes, what did we do? I gave you an introduction to solid-state materials in the first lecture. I also talked to you about the choice of the course title, why we chose this title and how that is relevant in today's world. In the second lecture, we gave you the introduction to a class of materials which are termed ceramics, and we also talked about the classifications and the application of these ceramics. we have given you two sets of materials, solid-state materials Now, if you look around, we have given you two sets of materials, solid-state materials and then ceramics. If we go forward a simple question will come in a curious mind like suppose I mix two solid materials, then what will happen to that? And that is where the genesis of today's lecture lies.

We will be introducing to you the concepts of composites which are basically a mixture of two or more than two types of materials, and then they are brought together, and the property of the final compound is very different from the individual compounds. So, it is not like you will get properties of individual compounds; there will be a convoluted property, which you will see when we make these composites. So, just like in the previous lecture, let us start by defining what composites are, classify the composites into various subheadings and see which ones would be relevant to this course. Finally, we will talk about the applications of these composites. As I said, we had talked about ceramics in the previous lecture.

In today's lecture, we are moving a step forward by introducing the concept of composites. You will find that these composites are not random, and it is not that they are being fabricated for fun. They are actually finding applications from toys to stealth bombers, from automobiles to aircrafts, from shoes to jackets. So, it is not that composites are something that is random; you mix any two materials randomly, and you will get a property. Even the choice of the materials that you will have to make such that they come together to give you a desired response is a well-defined flowchart.

It is not random, I repeat. What is a composite? Let me first define. A composite is composed of two or more than two distinct phases. So, there are two distinct phases that you are trying to bring together. One of these phases is called the metric phase, while the other is called the dispersed phase.

We will discuss about these matrix phases and dispersed phase a bit later, but just to give you a brief overview, the matrix phase can be understood as the parent lattice in which the dopants are coming or that system which is going to get dispersed in this parent phase are called the dispersed phase. So, you have a large room in which you will be putting some chairs, for example. So, the room will become the matrix, and the chairs will become the dispersed phase. So, I hope you have understood very broadly in layman language what the metric phase and dispersed phase mean. We will give you the scientific definition in a few slides from now.

So, composites are what? They are composed of two or more than two distinct phases, and they have bulk properties which are significantly different from those of the constituents. So, it is not like you will have individual phases also giving their properties. So, it is not that when you make a composite, you will see certain properties of the matrix phase and certain properties of the dispersed phase. No, there will be a convoluted property that would be very different from what you will see from individual components. So, when you combine two or more materials to form a composite, one of the materials is called the reinforcing phase.

This reinforcing phase can be in the form of fibers, sheets, or particles or they can be embedded in other materials, which is called as matrix phase. So, these reinforcing phases will go into the matrix phase. So, that is basically the dispersed phase. The reinforcing phase and the matrix materials can be of various nature and characteristics. For example, you can have them as metal, you can have them as ceramic, or you can also have them as polymers.

The details of polymers will be covered in the next lecture. So, it can be metal-metal composites. It can be metal-ceramic composites, it can be ceramic polymer composites, it can be polymer-polymer composites. So, you can have various combinations possible to make composites. The dispersed phase is usually stronger than the matrix. It is used usually, it is not always true, but usually, the dispersed phase is stronger than the matrix, and therefore, it is called the reinforcing phase.

Now, I have defined the composites, and we also heard that you can have various compositions of the dispersed phase and the matrix phase like metal-metal, metal-polymer, and ceramic-polymer. Based on this combination or these combinations, the composites are classified under various subheadings. They are metal matrix composite that is MMC, polymer matrix composite PMC and ceramic matrix composite CMC. For us, the composite that is ceramic matrix composite CMC would be relevant because that is the logical way forward because we have studied ceramics in the previous lecture. So, we will take them as an example and describe the details of composites and how the properties change as we go from one composite to the other.

The MMCs are composed of a metallic matrix. That means you have a metal as the matrix. So, the parent matrix and a dispersed, dispersed ceramic. So, you have a dispersed phase, which is a ceramic or it can also be a metallic phase. As you can easily understand, what would be the polymer matrix composite, if I ask you to define you should be able to easily answer ok.

What would be a polymer matrix composite? It means that it will have a polymer as the matrix. So, you will have a polymer as a matrix. It can be from a thermoset-type polymer, or it can be a thermoplastic polymer and the embedded or the dispersed phase could be like embedded glass, carbon, steel, Kevlar or any other type of fiber as the dispersed phase.

Coming to the third one, that is ceramic matrix composite, what would be the matrix phase? You will have a ceramic as the matrix, which is evident from the title. And the embedded phase is fibers or whiskers of other materials.

This forms the dispersed phase in CMC. So, based on the parent phase, the bulk phase, you define the classification of composites. So, let us move forward and tell you further why I am taking this CMC as an example. What have we learned in the previous lecture? Ceramics are hard, and mechanically stable, they are refractory type materials, they can withstand very high temperatures, and they are chemically quite stable. So, using those properties that we discussed about ceramics in the previous lecture, we would like to move forward.

But these are hard materials, these are very hard materials. So, as we go towards the applications where we talk about wearable electronics, flexible electronics, systems which should be flexible, they can be placed anywhere, they can be folded, they can be folded in a way that you want to carry them into small bags and then open it again just like your foldable mobiles or rollable TVs. You want systems that are flexible; that is where today's world is moving. You need systems that are based on flexible electronics. But ceramics are hard, so what will you do? They you need to answer the limitation of the inherent brittle nature of these ceramics. And that is where you get CMCs coming into the picture.

So, what do you do? You actually combine the ceramic matrix material with suitable fibers, some kind of fibers. This leads to flexibility in the system and then if you can get additional and interesting properties out of these composites, then this would be the way forward. And that is what has made the CMCs an interesting class of composite materials. So, what would be the components of CMCs? Obviously, you have a matrix, you have a fiber and there are interfaces. This is the third term which you will hear in this.

So, what are fibers? Fibers provide strength and structure for ceramic composites. And you can have two-dimensional fibers or three-dimensional fibers. You can have woven fabrics in continuous fiber-reinforced CMCs in addition to the matrix which would be ceramic as we have discussed earlier. We would also like to know what the term interface means. The interface provides a weak interfacial bond to the fiber and matrix, allowing for the slipping and energy dispersion of the mechanical stresses experienced in the composite. This seems to be a very difficult thing to understand.

Let me make it simple. Suppose this is a pen. If I have to disperse this pen in a polymer matrix, let us take this hand as a flexible polymer matrix; then what are we going to do? You put a pen here, but if I lift it, the pen will fall, right? So, you have a system as long as it is horizontally placed; it is stable. But the moment I make it vertical, the two systems get separated. So, you have phase separation. This is not a stable material. What do you need? Even if I have a horizontal or vertical alignment of this composite, the two phases must not get separated.

How will you do it? That is where this interface comes in. It comes in a way that it provides weak interactions between the two phases that is the fiber and the ceramic in this case and they remain in a compact state. They remain attached, but please remember that it is not a chemical reaction that is taking place. There is no change in the molecular formula of the individual components. It is just the physical binding which is taking place.

So, the individuals remain as individuals, but they are being forced to come together by this weak interfacial bond that is introduced by the third component that we are calling as interface. I hope this concept of interface is clear now. If not, then we will discuss it further in the online session. So, the CMCs can have fibers that can be of different types. They can be fibers based on oxides or non-oxides.

These fibers are of low densities and high melting points, and you are making them how? You are actually taking a material and pulling it in one direction. Therefore, the diameters of these fibers range from 10 to 20 microns. It is the diameter of the not the length of the fiber, not the length of the fiber. The length could be in meters or centimeters or in between fiber, but it is the diameter which is in the range of 10 to 20 microns. So, this is why the point about fiber must be very clear to you.

The Young's moduli of these fibers are relatively high because you have areas that are much smaller. So, tensile stress upon tensile strain. So, you will get what? You have forced upon delta L by $L_{0,}$ and as A is small, you get Young's modulus which is very high hence if you have Young's modulus which is high that means, it will provide high strength, high mechanical durability to the whole system because the high strength material is fiber and this fiber is now allowing the brittle ceramics to get dispersed in different places, but the brittle nature characteristics are being countered by the high strength fibers. You can make fibers using various techniques. This will be discussed in the second week when we start talking about the synthesis protocols, but the most common techniques which are used to make fibers are spinning and chemical vapour deposition.

Now, the most common example you have seen around is the making of the sugar candy which you have seen when you go to a Mela or you go to any other market, and now you see that there is a sugar candy being made. So, what is the person doing is taking a sugar syrup and then rotating at a very high-speed using a spinner and then trying to take the fibers out and then roll it on a stick and then giving you to eat, and that is a conventional example of the electrospinning or spinning technique to make fibers and that is fiber which all of us have seen around. Similarly, to the earlier case that is the fiber the matrix itself can also be of two types. It can be a matrix based on oxide materials and a matrix made up of non-oxide materials. Why do we classify it into oxides and non-oxides? The answer mostly lies in the strength of the materials and the temperature at which they are formed.

The oxide materials are mostly formed at very high temperatures, and they are quite hard whereas, the non-oxides can be relatively formed at a lower temperature, but they continue to have high strength. So, it is not the strength that is being compromised it is mostly the fabrication temperature that is being modulated in two types of materials. Let us quickly revise about CMCs. So, in CMCs the matrices are designed to have high thermal stability with a similar thermal coefficient of the fiber and a low density of the composite. Why should we have a similar thermal expansion coefficient of fiber and the matrix? Why? Can you think about it? Let me give you an example.

Suppose, I take this hand and I take the other face which is the second hand which is forming a fist. Now, if this composite is heated and this hand starts to expand this starts to expand whereas, the second phase is not expanding at the same rate. What will happen? There will be a gap in the middle because the one that is expanding much faster will expand and become larger and the other is unable to fill the gap that is being left behind by the second phase which is expanding much faster. If that is happening what will happen? You will again have phase separation and the composite will become unstable. Therefore, a system must have similar thermal expansion if you want to have it in a stable configuration.

The matrix which is made up of ceramic provides protection to the fiber as well as protection to the interface by means of what? By means of energy from mechanical stresses that can disperse through the lattice. So, if you have high stresses moving through the composite, it is being absorbed by the matrix not the dispersed phase. We have already seen that the coefficient of thermal expansion will play an important role. Otherwise, you will start seeing cracks, you will see undue stresses, and that will damage the CMC. It is not that why should we worry about this thermal expansion coefficient.

If I have a composite that is being used, let us say even for a wearable electronic which is being pasted on our shirt like motion sensors which is routinely being done, or you want to have any kind of sensor on your body which is sensing the glucose levels in your body. Now, if you those are not stable as a function of temperature, then what will happen? Suppose a person on a winter day when the temperature is around 0 degrees is walking on a road. Then the same person with the same sensor on the shirt works on the same road, but the temperature is now touching 50 degrees which is now routinely seen in India. Then you have a difference of 50 degrees, and if the thermal expansion coefficient is very high, then the sensor as a function of these temperature variations or cycles will have phase separation, and it will stop performing in a manner that you actually desire. It is hence very important that it is hence very important that the materials must have low thermal expansion coefficients and be able to form stable composites.

As I mentioned the synthesis procedures for ceramic matrix composites are quite a few. Some of them could be based on sol-gel, chemical vapour infiltration, liquid phase infiltration, the polymer infiltration or you can have thermal cross-linking followed by pyrolysis. Hot pressing techniques you can have exfoliation followed by ball mill. We will discuss them in the coming weeks, but the common technique that is routinely used is chemical vapour infiltration is shown on this slide. This slide clearly shows the formation of a silicon carbide synthesis protocol.

Without going into detail, I repeat that we will discuss about them in the coming week. Once we have formed the CMCs, it is imperative that we find the range of applications for these CMCs. And if you look around these CMCs have a large number of applications. They are routinely used for aeronautical or automotive purposes. They are being used for biomedical applications, orthopaedic or even dental implants.

The common dental implant that you see or many of you may have actually gone to a dentist and got your cavities filled, it uses zinc oxide as the dispersoid, or earlier it was basically the matrix. But now you have inomers where zinc oxide or titanium dioxide are dispersed. Then you have composites that are being used for petroleum hydro treatments. You have potential absorbance for chemical warfare. So, these can absorb hazardous gases, and therefore, they can be used in various places.

They are being used in solar cells, flexible solar cells, you have flexible TVs, you have flexible phones, you have flexible pens, you have flexible cameras. These are the applications of these CMCs. Over the last decade or so, as the pollution levels are being monitored closely and we want to live in a condition in ambient condition that is ideal, we also want to maintain the humidity levels in our rooms, therefore, these CMCs have been investigated and they have delivered exceptional performance in humidity sensors. In addition, there are much more intricate applications of these CMCs. They are used in flexible electronics, fuel cells, cutting tool applications, gas turbines or insulators, and both electrical and thermal insulators.

Why? Because if you have ceramics, the matrix space, then those ceramics are insulators and therefore, they can be used in insulators both for electrical and thermal insulating purposes. What have we learned today? That composite materials are there; just like ceramics, we are surrounded by composites. There are various types of composites, but for us, ceramic-based composites are very relevant, and they have a large number of applications, which were also discussed in the final part of this lecture. These are the references that were followed to prepare this lecture.

I hope you enjoyed this lecture. In the next lecture, we will go forward and introduce the third class of materials which is polymers. Thank you very much.