Carbon Materials and Manufacturing
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Lecture - 03
Story of Carbon: Carbon on Earth and in Outer Space

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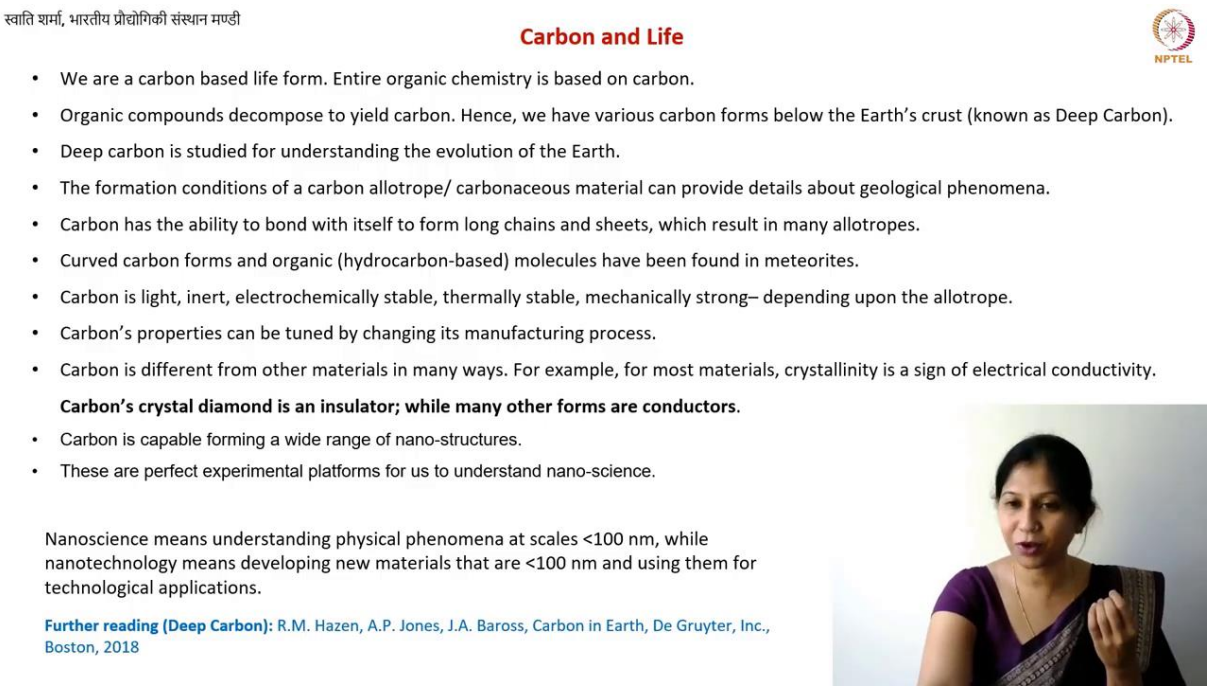

Hello everyone, now we start talking specifically about carbon materials, about the atom of carbon and so on, but in general because our next couple of lectures are going to be more of introductory nature, I am going to discuss why we need to understand carbon at all? What is the importance?

So, many of you who are attending this course might be from manufacturing background, engineering background, some of you might be also from chemistry background, many of you might be research scholars who are conducting your research in the field of carbon or maybe you are working on one specific carbon material and not on all carbon materials.

So, we need to understand why we are doing all these and why carbon has been a very important technological material for a very long time. It is not just that we only recently started working on or started doing carbon related research. Even if you pick up a book which was written 50

years ago it would still say carbon is a new, but old material and if you pick up a book or research article written very recently it will say pretty much the same thing.

So, the fact is that carbon is a material which has been very interesting for scientists and for technological applications as well for a very long time. And people are still surprised when a new carbon material comes up because it may actually have so many different properties. So, it is a material which always surprises you with its wonderful properties. Now, why do we have these wonderful properties and what are the things that we can do with these properties?

First of all, if you think about the title of this slide, I have given carbon and life. You know that we are all made of carbon practically, not just carbon, but organic material which is primarily carbon. So, we are carbon-based life forms. Now, maybe there is some silicon-based life form, but let us stick to our planet.

What happens when people die or when you know when animals die or when trees die? This organic material converts back into carbon. What does that mean? That you lose all the non-carbon atoms from these organic materials and then what you get is elemental carbon. What happens to these non-carbon atoms like hydrogen and nitrogen, oxygen? They either form gases or they somehow get mixed back and they go back to the environment.

Now this is obvious that a lot of things that we have on earth are going to contain carbon, are going to have certain forms of carbon in them or they are going to yield certain form of carbon. So, this material we cannot avoid. This is one of the very fundamental elements.

Carbon is one of the fundamental elements. It is also a small element and I am going to tell you that in the red giant stars, you are going to have some of these carbon atoms that are being formed or being generated as a result of nuclear reactions.

So, you have a lot of carbon on earth and that is why it is important for you to know anything related to understanding life or understanding evolution on earth. Now, any organic compound as I said when it decomposes it yields a certain form of carbon; it will always.

You know about petroleum or different forms of carbon that you mine for example, coal. So, where does that come from? You know that maybe a long time back there were animals, trees and because of heavy tectonic movements, they got buried under the crust of the earth and because over a long time, due to high pressure, temperature and extreme conditions they

converted into carbon. What does that mean? Again all non-carbon atoms left those materials due to whatever extreme conditions and then you are left with carbon. And what we also do for technological applications we try to mimic these extreme conditions in many ways.

Now these forms of carbon which are buried under the earth or which now have converted into not just coal and petrochemicals, but also into diamonds and graphites. So, one question arises is why some carbon forms or some organic materials converted into graphite while the others converted into diamond and some remained coal or some did not completely lose all their organic material and they then formed petrochemicals?

Even petrochemical is a very vast field of study. It's not just you have these diesel and petrol. You have many other chemicals, many other solid forms of carbon, many semi-solid forms of carbon. So, you have many petrochemicals.

You also have gaseous forms of carbon. Why did some organic material convert into a different form than the other? All of these carbon materials that are below the earth's surface, these carbons are collectively known as deep carbons.

So, deep carbon is a completely different field of study. Why do we study deep carbon? Because this can give us some clues on how the earth evolved. As a planet, what was there several million years ago and how did carbon and many organic materials form and what happened also.

Now, at several time points various tectonic movements took place, sudden environmental changes took place and all of these things can be understood by understanding the structure and properties of these carbon materials.

And carbon materials is not just about the study of carbon, is not just limited to manufacturing purposes or technological applications. There are so many other things that we can understand, if we know how to analyze our carbon, how to understand the properties or how to correlate the structure and property of carbon.

Deep carbon as I said, is a completely different area of research and there is one reference that I have provided here. In case you are further interested you can access this book (refer slide). Now, how do we learn these things? As I said you need to correlate the structure and properties of material.

Now, here I have two new terms let say, one is allotrope and the other is carbonaceous material. So, allotropes are crystalline forms of carbon. We will discuss allotropes in detail. We will also discuss what should be the definition of allotrope, how this definition has changed over time and should we include a few new carbon allotropes also, just for a better understanding.

Allotropes are basically different forms of elemental carbon, typically, different physical forms or different crystal forms. Now, we have these different carbon allotropes like diamond, graphite and fullerenes. What are carbonaceous materials? Carbonaceous materials are basically materials that have a lot of carbon content, primarily organic materials. In short anything that is carbon rich is known as carbonaceous material. Now, we can understand these carbonaceous materials and allotropes that we find inside the earth then we can understand different biological phenomenon. We can also study the calcium carbonates that are under the seabed. These calcium carbonates also contain certain forms of carbon.

There are not just carbon materials, but also other elements that people study of course, to understand the evolution of earth, but carbon plays a very important role because well again we are all made of carbon.

Now, the one good reason for the formation of this long chain or long sheet like molecules and all these organic molecules, is the fact that carbon can bond with itself. In fact, carbon really likes to bond with itself rather than with other elements. Carbon really prefers to make bonds with itself that gives it a more stable geometry.

And these bonds you can call it sometimes self-polymerization, but technically we use the term polymer when you have a monomer. Here we have just a lot of carbon atoms and they are joined together. So, no matter how you want to understand the point, there are a lot of carbon atoms.

They prefer to form bonds with each other and they form very long and massive structures. So, this is one ability of carbon because of which it helps in the formation of organic material because a lot of organic materials are basically polymers biopolymers.

You already have diamond and graphite. You also have certain curved forms of carbon. You already know that fullerene or buckminsterfullerene is a spherical structure, but you will also hear the term fullerenes sometimes for structures that are not spherical, but they have a strong curvature.

So, in this lecture I am going to use the term curved carbon in order to differentiate between buckminsterfullerenes or any spherical fullerenes and other fullerenes. When we call fullerenes, we are talking about spheres and for any other curved structure I will just use the term curved a carbon.

Now, these curved carbon forms and also certain carbonaceous materials organic material hydrocarbons have also been found outside of the earth. So, I already told you that in the stars you have the formation of carbon, but sometimes when there is a meteorite that hits on the surface of the earth then you actually find carbon forms.

And because this hitting of the meteorite is a very high impact phenomenon that is why you have also sometimes these curved carbon forms. Because when there is an extreme condition, extreme pressure condition you often end up getting curved carbon forms. The energy of formation is pretty high, but natural events can actually lead to these formations. So, the point is that, this also will help you understand life outside of the earth within the solar system even outside the solar system. So, carbon has been found in many places outside of the solar system as well.

Each carbon material, each carbon allotrope will have a unique set of properties. However, one common thing among all of them is that these are light materials because the carbon atom itself is a light material. So, carbon materials tend to be light and they typically have very strong bonding with each other and that is why they also have good mechanical strength. Now, that is a subjective thing, for example, in the case of graphite one single sheet of graphite is pretty strong, but when you have a layered arrangement then the bond between the two layers is not that strong.

So, you may say that this is not mechanically strong, but then again it depends on at which scale you are talking. If you are talking only about the single sheet,then it is a very strong material. Diamond is still the hardest known material for technological applications.

We will talk about this single sheet of graphite or what you also call graphene, that in principle is stronger than diamond, but that has not yet a technological application plus you have the sheet like flake like structure. So, it is difficult to make cutting tools out of this material.

So, the point is that however, these carbon materials are mechanically strong and they are light. If it is an elemental carbon material, it's often inert. So, what is an inert material? In general,

that does not react with that does not you know chemically react with things. Coals have a very good absorbance, and they even burn and convert into carbon dioxide. Well, the point is that often when there is a conversion of carbon into other materials like carbon dioxide or any other chemicals that is due to impurities in carbon.

The elemental carbon materials are actually very inert. So, think about diamonds, think about graphite, the lead of your pencil that is actually a very stable, very inert material. You leave your pencil outside in humidity conditions or even if the temperature goes up and down they do not really react with anything. So, most of the elemental carbon materials actually have an inert surface. They also have good electrochemical stability, thermal stability and so on. All of these properties we are going to talk about, but these are some of the reasons that we study carbon.

Do remember that for each carbon allotrope the properties will slightly differ and sometimes they will differ drastically, but even with a small change in the manufacturing process you will get to know slight differences in electrical conductivity, electrochemical stability and so on.

But there are so many interesting properties of this material because of which we learn about these materials. And also the fact that by changing the manufacturing process you can actually change its properties. So, this is when it comes to manufacturing applications then it is also a very useful thing for us.

So, in a way we have materials where we can tune the properties which may not be the case with certain metals or elements or even alloys because you have a certain combination. You have a certain type of crystal structure, you have a certain type of material and you may not be able to change the properties too much, but in the case of carbon, you can actually tune the properties using by tuning the manufacturing conditions.

Now, yeah carbon is interesting, as I said that it always surprises people. So, there are many things about carbon that are very different from other elements. For example, carbon is electrically conductive, but not all forms of carbon are like the diamond is an insulator and that is because of its crystal structure. When we talk about crystal structure then we will discuss this, but the graphitic forms of carbon or the graphite-like carbons are electrically conductive, but on the other hand, you have another crystal which is a diamond that is completely insulating. This is because of the nature of bonding and many conductive materials are typically metals, for many conductors you have a good crystallinity, good crystal structure has a higher

conductivity. So, as the crystallinity increases then you get higher and higher electrical conductivity that also happens in the case of graphitic carbons, but not in the case of a diamond.

So, you cannot say just because it is a crystal it is going to be electrically conductive. You need to understand more than that. So, this is how carbon is different from many other metals. This was about the bulk carbon materials. When you think about nanoscale carbon materials again carbon has the ability to form these long-chain sheet-like molecules. It can also have rings of carbon, like hexagonal rings which are made of 6 carbon atoms. They can withstand certain stretching, vibration and strain which also means that they can survive even when they are not perfectly six-membered rings.

So, you see seven-membered rings or five-membered carbon rings in nature. Sometimes because of these non-six-membered rings, you get curved structures that are the reason for the formation of curved carbons and that is why you also have non-six-membered rings in a fullerene which is a football like molecule like a buckminsterfullerene.

So, because of this ability to be able to form different types of form of bonds, carbon can also make a lot of nanostructures. So, nanostructures are nothing but what we learnt in the previous lecture. Nanostructures are just structures that have a certain well-defined geometry at the nanoscale. Carbon also can form a lot of nanomaterials and that is the reason nowadays people study carbon so extensively.

We are able to understand the properties of nanomaterials. And all of these things are very easy using carbon because it can form a lot of very interesting nanoscale structures and when in bulk, you can call them nanomaterials.

So, I told you in the previous lecture that nanoscience basically is about understanding things at the nanoscale, how do the properties of materials change at the nanoscale, how do you know what is different when things become too small. When we talk about manufacturing as for engineers only the bulk materials are always important. So, the nanoscale, the same material at the nanoscale changes certain properties because of the higher surface and you do not have defects and so on. So, understanding these things is called nanoscience and using these materials for technological applications is called nanotechnology.

And typically when we talk about this nanoscience technology, the individual structural unit should be smaller than 100 nanometers. If there is something which is 500 nanometer in size

you will rather call it 0.5 micrometres rather than you will you know rather than saying 500 nanometers. I mean in principle you can even say 10000 nanometers, but then you do not call it nanotechnologies when you are talking about structures smaller than 100 nanometers.

Now, these interesting carbon materials like the single sheet of graphite have certain properties which were not really observed in other materials before. So, these carbon nanomaterials also provide a perfect experimental platform. There are things that you can sort of mathematically derive and physically understand like what kind of interactions should take place, how should the electrical conductivity change, how should the band structure change when you have a single layer thick structure, but at the same time how do you experimentally validate it. That is why materials like graphene have become very popular also among those who are scientists and not engineers, because of the fact that they provide a very interesting experimental platform for understanding science at the nanoscale.

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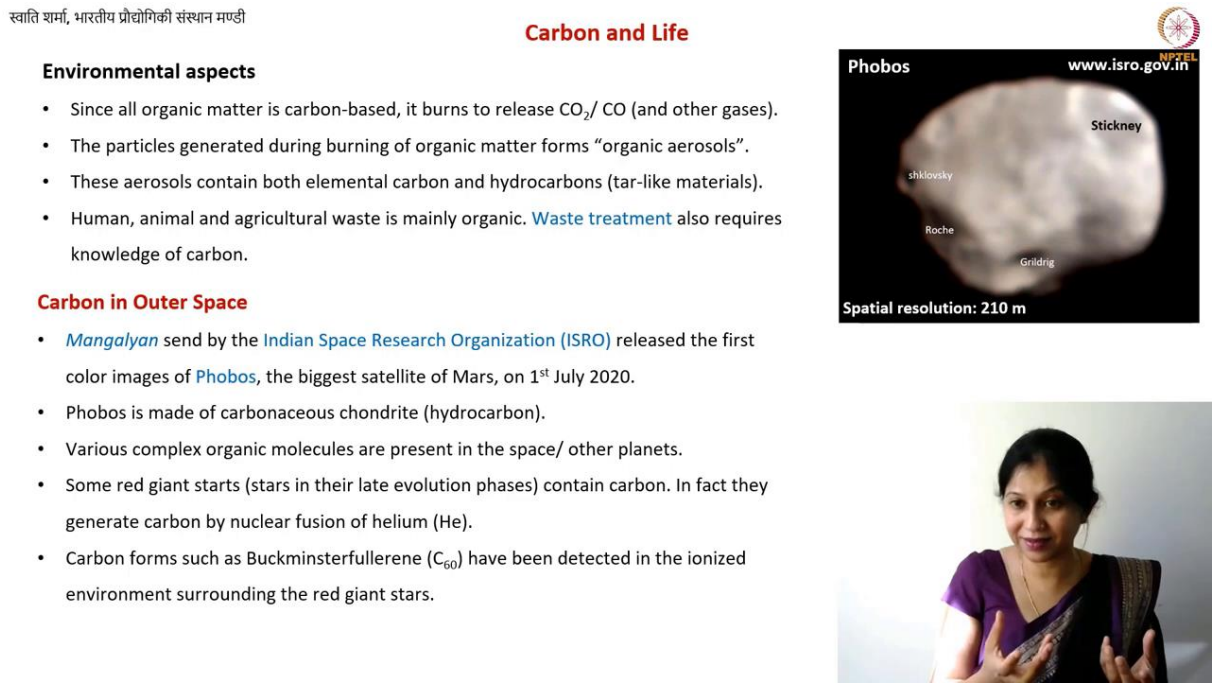

Now, this was about life and carbon, but how about the environmental aspect? So, I've included these environmental aspects because you hear so much about the carbon cycle, the carbon footprint and everything related to carbon and carbon-based technology.

We are living in a carbon-based life form, we have organic fuel and petrochemicals, which are also made of organic material, so everything is related to carbon. When you are going to burn this fuel that is also going to release some carbon.

So, I told you that carbon materials or organic materials would pretty much always decompose and yield some carbon. There is going to be some contribution of carbon in the environment. Of course, the imbalance is the problem and that is why when you have a lot of carbon dioxide and you do not have enough trees then this imbalance is dangerous.

And that is why all of us have indeed polluted the environment and we have created a lot of carbon that naturally would not be there. And that is why environmental pollution has a lot to do with carbon. And that is why even if you want to become an environmental engineer then it is very important for you to understand carbon structures, carbon materials.

So, you know that carbon dioxide and carbon monoxide are greenhouse gases and there are also some other gases, for example, hydrocarbon gases which are formed when you burn the fuel. You also have small organic molecules, they are slightly bigger than what you have in the gases, but they are still not so small that they will just remain in the gaseous form. Sometimes they settle down in the environment, sometimes they are very reactive. So, they end up attaching with other molecules in the environment. Sometimes you breathe them inside and they can be harmful to you. So now, where do these particles come from? When you burn organic matter like fossil fuel, agricultural waste, what happens at burning? Burning is the reaction with oxygen, but if you have excess or have a sufficient quantity of oxygen then you will get carbon dioxide. All the organic matter or most of it will convert into carbon dioxide.

But if you do not have sufficient oxygen or sometimes the burning is happening very fast. Even though there is a lot of oxygen in the environment, but because the reaction took place extremely fast then not all the organic matter was able to convert into carbon dioxide. In that case, you will also have carbon monoxide and you will also have some tar-like particles. So, these tar-like particles basically result from unburnt or semi burnt carbon particle or organic matter. These particles are heavier. So, these tar-like particles end up forming organic aerosols. Aerosols are basically like a colloidal particle in your environment and since these colloidal particles which also may attract some water in the air and they will be like droplets to some extent, which are suspended. So, they are not so light that they can go too high up, but at the

same time, they may not immediately settle down because they are not so light. So, these organic aerosols then contain carbon which may be either completely or highly burnt carbon.

So, you know it has relatively higher carbon content than you will call it black carbon and if you have these tarry materials then you rather have you often have a brownish color, then you will have what you know as brown carbon.

So, you can get both black carbon particles and brown carbon particles which are studied by environmental engineers and the concentration of these particles actually really tells you about what status of your pollution in your surroundings is.

We know that a lot of waste is generated on our planet; whether it is technological waste, whether it is plastics and polymers or whether it is organic waste, by the way organic does not always mean that it is natural. Anything which is formed by carbon, which is primarily hydrocarbon. So, all of these are also generated as waste. Now, since we are talking about the environment and the brown carbon particles, we should understand that the human waste or urban solid waste can be heated in a controlled environment in such a way that the non-carbon atoms leave when we induce the extreme condition.

If you do it in a very controlled fashion then you can stop these organic carbon particles from going into the air. You can rather catch them and then utilize them for some technological applications. So carbon is definitely very strongly related to the environmental aspects and especially environmental pollution.

Now, carbon in outer space; I already told you a few things about it. Carbon based materials have been found outside of the earth. Very interestingly this is a picture I have taken from the ISRO website. Also, you can go to the website and may be read more details about it. This is a picture taken by Mangalyaan and this picture is of one of the satellites of mars which is known as Phobos and this is actually a recent picture just in July 2020.

The Mangalyaan took this picture, and this is the first time any color picture of Phobos was taken by the way. And what is very interesting about it is that some carbonaceous materials were detected on Phobos. Now, what do these things tell you? If there is a presence of hydrocarbons; that means, there is a possibility of life, may not be human life, may not ne animal, maybe some very small organisms may exist on Mars as well as on Phobos.

So, this is where carbon becomes very important. You see just the presence of carbonaceous material can tell you so much about the evolution of a planet and you know so much about the solar systems and so many interesting things. Now, also in outer space, there are various complex organic materials and all carbon-based molecules that exist.

In the case of red giant stars that I had mentioned that previously, these stars basically look red because they are in their late evolution phase. They contain carbon and their environment contains carbon and you know how carbon is formed? You have hydrogen and helium that is formed due to the nuclear fusion of hydrogen. And if you now have two helium atoms fusing together then they first make a beryllium atom and then after that then there is a carbon atom formed in this nuclear process later.

So, there you see how elements are generated. At very high energy you have carbon atoms being generated in these red giant stars which of course, come together and sometimes they also form structures.

Often they have curved carbon structures like fullerenes and these have been formed and these have been found in several red giant stars or the environment surrounding the highly ionized environment surrounding the red giant stars, contains C_{60} or similar spherical carbon molecules.

And you know that these stars are also our source of carbon. This is where the element is being manufactured. Also, there are then certain analogues of fullerenes. Analogues means, you have some other chemicals let us say entity any other element, for example, attached on top of them. So, if you have hydrogen attached to fullerenes or hydrogen trapped inside the fullerenes then you would call them hydrogenated fullerenes and these are also believed to exist in many interstellar objects. You know that carbon is definitely found in outer space and that it does tell us a lot about outer space.