

Processing of Non-Metals
Prof. Dr. Inderdeep Singh
Department of Mechanical and Industrial Engineering
Indian Institute of Technology, Roorkee

Module - 6
Ceramic Matrix Composites: Processing
Lecture - 2
Ceramic Matrix Composites Fundamentals and Properties

Good morning to all of you, a warm welcome to this second lecture of module 6. Let us revise what we have covered in lecture 1 of module 6. We have seen what are ceramic matrix composites, but before going to the discussion on ceramic matrix composites we have revise the basic concepts of ceramics, which we have already covered in module 3 of this course on processing of non metals. We have seen that where the ceramic matrix composites fit in the broad family of composite materials. If you remember there was a diagram in which we have seen that the matrix in case of ceramic matrix composites is a ceramic material and the reinforcement can be of different types.

In reinforcement there are three sub categories we have seen on the basics of the shape of the reinforcement, we can have discontinues reinforcement or short fiber reinforcement. We can have viscose in the reinforcement, we can have long fibers in the reinforcement, then depending upon the orientation of the reinforcement we can have aligned reinforcement and we can have a random distribution of the reinforcement in the ceramic matrix. Also on the basics of the chemical nature of the reinforcement, we can have oxides say a carbides and in some case nitrides as the reinforcing materials.

So, basically in case of ceramic matrix composites just to revise what we have already covered in lecture 1 of module 6, we have only covered that what are the basic aspects of ceramic matrix composite and what are the basic advantages and limitations of the ceramics which are overcome by the ceramic matrix composite. So, we will take our discussion further related to the fundamental aspects of ceramic matrix composite and we will see that what are the challenges for the ceramic matrix composite.

In the process we will try to understand that what are the important properties that we should always consider when we are talking about or when we are advocating the use of ceramic matrix composites in certain applications, so there is a list of properties that we

would be covering today. And one of the important aspects that we have covered in lecture 1 was the fracture toughness. It was highlighted that the fracture toughness of ceramics is less and that is one of the major challenge for the application of ceramics in many engineering application.

It was seen that by the addition of reinforcements in the ceramic matrix the fracture toughness can be improved. Now, we will today try to understand that how, when we put the when we put reinforcement in the matrix what are the various types of toughening mechanisms? How the fracture toughness of the monolithic ceramics matrix improves by the incorporation of the reinforcement? There are a number of toughening mechanisms, but we will try to understand two or three basic toughening mechanisms with the help of a diagram.

So, in today's lecture our focus would primarily be on the fundamental aspects of ceramic matrix composites and the properties of the ceramic matrix composite. Towards the end of today's lecture our focus would be towards the various processing techniques. In the previous lecture I have given a broad over view of the processing techniques which are used for processing of ceramic matrix composites, but in today's lecture we would be focusing on certain or we would be outlining certain techniques which we would be covering in our subsequent lectures in this particular module on ceramic matrix composite.

Finally, we will see that why secondary processing is required, because once we get a shape of particular product, which is made up of a ceramic matrix composite, sometimes we need to certain secondary operation in order to improve the versatility or you know order to improve the functionality of the CMCs or the ceramic matrix composite product. So, why secondary operations are required and what we can achieve by this secondary operations, that is going to e the last part of the today's discussion. Finally, we will see an important aspect that why not much work or why CMCs are still in the development stage?

What are the important challenges in case of ceramic matrix composites and both the challenges are related to the high temperature applications of the ceramic matrix composites. So, with this introduction to today's lecture and a brief review of the

previous lecture let us now start our discussion on the ceramic matrix composites, there fundamental aspects and their properties.

(Refer Slide Time: 05:31)

The concept of Ceramic Matrix Composites (CMCs) aims at improving the desirable properties of ceramics with adding reinforcements as well as limiting their inherent weaknesses

IMPROVEMENTS OVER CERAMICS

- Degree of anisotropy on incorporation of fibers
- Increased fracture toughness
- Elongation to rupture up to 1%
- Higher dynamic load capability

The basic concept of ceramic matrix composites aims at improving the desirable properties of the ceramics with adding reinforcements as well as limiting their inherent weaknesses. So, if you just have a over view of this statement, it gives us an idea that why do we need to reinforce the ceramics? Ceramics is the well existing science and engineering ceramics are in use for more than 100 years or even more than that because different types of clays are in use, for so many years. So, the concept of ceramic matrix composites aims at improving the desirable properties of the ceramics. Now, let us stop at this particular point.

So, what are the desirable properties of the ceramics? If you remember in our previous lecture that is lecture 1 in this particular module, we have compared the properties of the ceramics and the metals. If you remember there are few properties like the hardness, the melting point, which is higher for the ceramics. The melting points of ceramics is higher, the hardness of the ceramics is higher as compared to the metals. On the other hand the density of the ceramics is lower as compared to metals, as well as thermal conductivity of ceramic is lower. the electrical conductivity of ceramics is lower.

So, there are few properties which are higher in case of ceramics and there are few properties which are lower than that of metals. But, all these properties in totality

advocate the use of ceramics in certain particular applications. So, ceramics are in use where all these properties provide them distinct feature which highlights, there uses certain applications. For example, let us take example electrical insulations. So, ceramics are used in electrical insulations why? Because there electrical conductivity is less, they are used for thermal insulation also, because there thermal conductivity is less.

So, what do we mean to say here? That ceramics also have got numerous applications because of some of the properties which we have already highlighted. They can be used for wear resistant applications also because of the high hardness, because of less density they can be used for light weight applications. So, all these properties high hardness, high melting point, low density, poor thermal conductivity, poor we can say electrical conductivity, all these properties have certain applications. So, ceramics by themselves have got lot of applications, but if you remember we have seen that there are few challenges also for the applications of ceramics. One of the challenges is the fracture toughness.

So, the fracture toughness for ceramic is less. So, they are not used for structural applications or where a lot of load is going to act on the ceramic product. So, they are basically avoided in case of load bearing applications. So, in order to improve their application in those particular applications also, in order to improve their use or increase their use many fold in structural applications or other applications where they may be required to takes some load also, they have to be toughened or they have to be reinforced with certain reinforcements. So, reinforcements can be different types of ceramics in different forms.

For example the reinforcement can be in terms of fibers the reinforcement can be in terms particles or the reinforcement can be in terms of viscose. So, the first important point is very, very clear why there is a need to develop or concept of ceramic matrix composite. So, let may read the point the concept of ceramic matrix composites aims at improving the desirable properties of the ceramics. So, ceramics by themselves have got certain desirable properties which I have already highlighted with adding reinforcements.

So, whatever desirable is already present in the ceramic, that we want to improve by adding certain reinforcements. We want to do away with the limitations which the basics ceramics or the monolithic ceramics posses. So, the last point is limiting their inherent

weaknesses one of the weaknesses is fracture toughness. So, that weakness we want to address by putting certain reinforcements into the ceramic matrix. So, these particular sentence gives us an idea about the concept of ceramic matrix composite that with what idea or what was the need of developing the ceramic matrix composite.

We want to improve the properties of the ceramic, we want to we can say further improve the applications spectrum of the ceramics by improving their properties and minimizing their limitations. So, for that the reinforcement is added into the matrix, so that the applications spectrum of the ceramics can improve further. So, what are the improvements over ceramics by the incorporation of reinforcement. So, one is the degree of anisotropy or on incorporation of fibers. So, when fibers are added and all the fibers are aligned suppose in one direction.

So, we have a directional reinforcement all the fibers are in one direction only, so the properties that would be there in that particular principle direction would be considerably different from the properties in the transverse direction to the direction of fibers. So, that will incorporate degree of un isotropy. So, the properties when there different in x y and z direction the degree of un isotropy would be higher. So, when we incorporate the fibers we can manipulate the properties of the resultant ceramic matrix composite and we can see and we can use it for a particular application in which we want to have difference in properties in x y and z direction.

So, basically by the incorporation of fibers and making a ceramic into a ceramic matrix composite we incorporate a degree of un isotropy in the product or the degree of un isotropy in the ceramic matrix composite. Second important point by incorporating the fibers with hand to increased the fracture toughness of the monolithic ceramic. So, which is one of the major limitation of the ceramics it is over come by putting reinforcements in the form of fibers or viscose into the ceramic matrix.

So, we try to increase the fracture toughness of the ceramics then elongation to rupture up to 1 percent, so in case of monolithic ceramics, how it fails? We will try to understand with the help of a stress strain diagram and in case of ceramic matrix composite, the specimen or the material under goes certain elongation before failure. Whereas in case of ceramic it has the certain failure all are catastrophic failure. So, in case of ceramic matrix

composite we will have a non catastrophe type of failure whereas in case of ceramics we will have a catastrophe failure.

So, in that is a point been addressed here that is elongation to rupture up to one percent. So, the CMCS specimen will elongate up to a particular level. Then it will finally fail, that we will try to understand when we will see the mechanical properties of the ceramic matrix composites. Finally, the higher dynamic load capacity, so the load bearing capacity and as well as the dynamic load bearing capacity of the ceramic matrix composite would increase as compared to the ceramics. So, when the ceramics have been reinforced with additional reinforcements or with different types of reinforcement the load bearing capacity.

Specifically the dynamic or the time bearing load bearing capacity would improve. So, particulars slide is very important because the question may be ask if you talk about that, I have a information related to ceramic matrix composite. The first question that would be asked is how CMCs are better than the ceramics? For that you need to answer the question pointing out all these aspects of ceramic matrix composite and just would revise we can say that we can manipulate the properties of the composite in x y and z direction also. In case ceramic matrix composite this point, we have already seen in a previous module where we have seen the polymer matrix composite, that the properties are different in x y and z direction.

So, similarly, in case of ceramic matrix composites also we have a property difference in x y and z direction. So, we can manipulate the properties, so we can incorporated degree of an isotropy in the material depending upon the specific desired designed requirement, where we have to manipulate the properties in different directions. We want different property in x direction a different property in wide direction. We can do it by aligning the reinforcement n a particular directions.

So, an isotropy is there in ceramic matrix composites increased fracture toughness as compared to ceramics elongation to rupture is there. No catastrophic failure takes place and finally, CMCs CMCs have got higher dynamic load bearing capacity. So, CMCs have got certain celliant advantages over the monolithic ceramics. Therefore, the applications spectrum or the use of ceramic matrix composites is increasing day by day and thee use for many sophisticated applications.

(Refer Slide Time: 15:57)



Advantages

- High hardness
- Hot hardness
- Stiffness
- Compressive strength
- Lower density

Disadvantages

- Low toughness
- Prone to thermal cracking

Now, whatever we have discussed, let us just revise and highlight that what are the advantages of ceramic matrix composites. So, you can see they have got high hardness hot hardness which I have explained in lecture 1 in this particular module only. That they have the tendency to retain their hardness at elevated temperatures also. It means that whenever the temperature would be higher in use when the CMCs is being put into use, and the temperatures are higher during in service they will retain their hardness. So, that is the property of hot hardness.

So, CMCs have got high hardness, they have got the property of hot hardness, they have better stiffness has compared to the monolithic ceramics or simple ceramics, the compressive strength is also better because of the incorporation of the fibers and the density is also good. So, these are some of the advantages of the ceramic matrix composites. So, disadvantages can be certainly because the matrix is a ceramic matrix the toughness is not comparable to that with the metal matrix composites.

Although metal matrix composites is not within the scope of our course because our course focus is on the processing of non metals and we are not going to cover the metal matrix composites because there the matrix is a metal, but on comparing the metal matrix composite with the ceramic matrix composites, the toughness of CMCs is lower has compared to the metal matrix composite. Sometimes they are proven to the thermal

cracking also because they have certain thermal stresses which are developed in CMCs during the processing.

Why this thermal stresses are developed, that we will see towards the end of today's lecture. Where we will see that, what are the challenges in front of the people or researchers who are involved in the design and development of ceramic matrix composites. There are few challenges that we will see and this thermal cracking is one of the challenges. So, that is one of the limitations of ceramic matrix composites. So, in this particular slide we have seen that what are the advantages of CMCs and what are the limitations of CMCs.

Just to revise CMCs have got high hardness, they have got the property of hot hardness, they are stiff good compressive strength and they have got lower density. When low density is an issue we can always advocate the use of such materials for light weight applications and ceramic matrix composites are finding huge applications where light weight is the primary designed criteria. So, the limitations basically are low toughness as well as CMCs are sometimes proven to thermal cracking.

(Refer Slide Time: 18:46)

Examples of CMCs

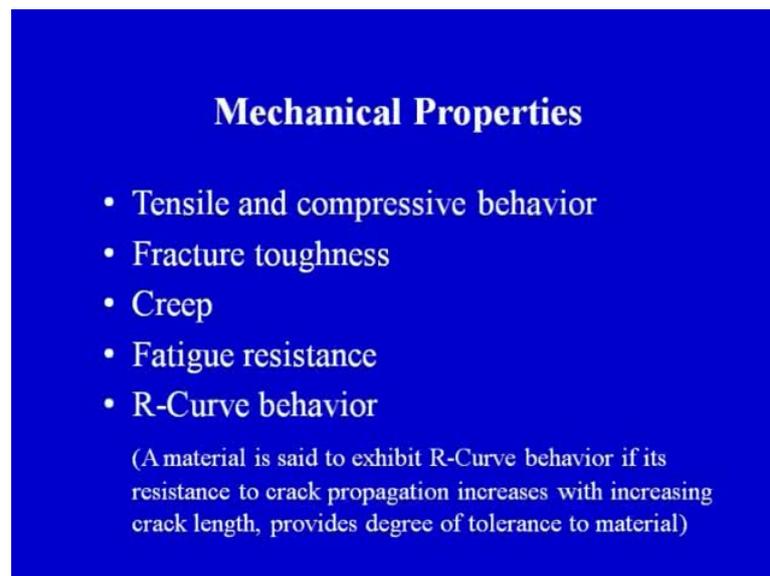
- Continuous SiC fiber reinforced glass-ceramics
- Zirconia-toughened and SiC whisker toughened alumina
- Carbon-Carbon composites

Now, this is just an some examples of CMCs continuous silicon carbide fiber reinforced glass ceramics, which can be one example of CMCs. We have a matrix and it has been reinforced with C continuous V fiber zirconia toughened and silicon carbide whisker toughened alumina. So, alumina is the matrix material here and silicon carbide whisker is

the reinforcing material carbon, carbon composites in which the matrix is also a carbon and the reinforcement is also done by a carbon or a carbon fiber.

So, basically these are few examples of CMCs there can be numerous other examples in which, we would be seen when we will discuss the processing techniques of ceramic matrix composites, because our focus primarily is on processing. When we will see the various processing techniques we will see that which type of matrix can be used for, use for this particular technique and what would be the reinforcement or what are the different types of reinforcement that can be used by this process? So, that we would be covering there, but this is just to give you an idea that what are the different types of reinforcements? So, we can carbon can be used as a reinforcement, silicon carbide fiber can be used as a reinforcement, silicon carbide viscose can also be as a reinforcement. So, these are few examples of ceramic matrix composites.

(Refer Slide Time: 20:08)



Mechanical Properties

- Tensile and compressive behavior
- Fracture toughness
- Creep
- Fatigue resistance
- R-Curve behavior

(A material is said to exhibit R-Curve behavior if its resistance to crack propagation increases with increasing crack length, provides degree of tolerance to material)

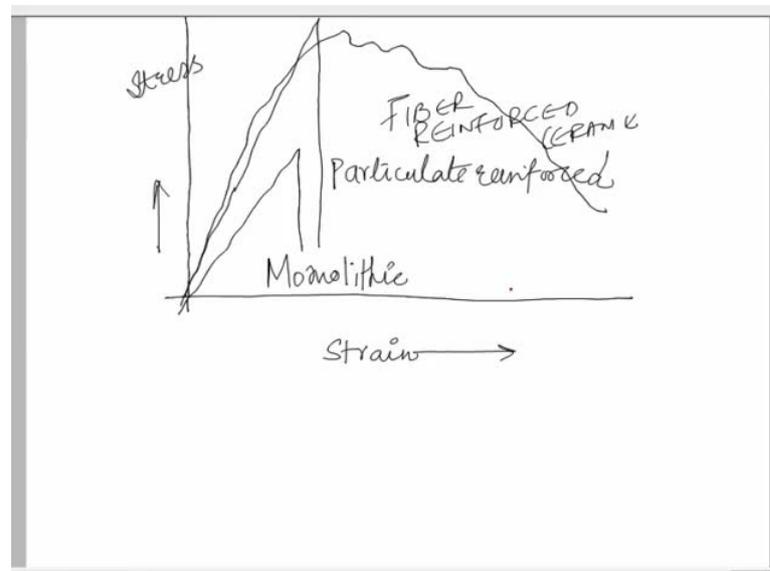
Now, coming on to the mechanical properties. So, on your screen you can see the important mechanical properties that we should always keep in mind, when we are advocating or when we are studying the ceramic matrix composites. So, first and foremost is the tensile and the compressive behavior, fracture toughness, creep fatigue resistance and the R curve behavior. These are important mechanical properties which have to be investigated before advocating the use of a ceramic matrix composite for a particular application, because in the previous slide we have seen few examples of

ceramic matrix composite. There is ceramic matrix composite it is a huge family and there are a large number of reinforcements which can be used, there are a large number of matrices or matrix materials which are used.

So, there is a combination of the matrix and the reinforcement, we have number or types of matrices we have types of reinforcement. So, for any particular combination we have to look into the mechanical properties of the ceramic matrix composite or the resulting ceramic matrix composites by the blending of the two constituents together. There two constituents are the matrix and the reinforcement.

Because there are large numbers of combinations possible we cannot discuss the mechanical properties of each and every combination, that how it would behave? But in general we can discuss that what are the important mechanical properties, which are important, in case of ceramic matrix composite. So, tensile and compressive behavior we can see, but tensile testing of a specimen can be done. How it will behave let us try to understand it with the help of a diagram.

(Refer Slide Time: 22:05)



So, on your screen you can see whenever we are doing the testing of particular specimen we can get a stress strain curve, that I am going draw on your screen. You can see we have one x axis, we have strain and on y axis, suppose we says stress. So, we have stress and strain on y axis we have stress and on x axis we have strain. Now, how are ceramic would be halved when it is tested. So, there would be sudden failure of a ceramic

material. Now, this is we can say how monolithic ceramic would be halved whereas now in case of ceramic matrix composites we are reinforcing the ceramic with a reinforcement.

If you remember the reinforcement can be in terms of particles or it can be in terms of continuous fibers. So, we can have continuous fibers in the reinforcement we can have particles in the reinforcement. Now, let us take the ceramic which we have already drawn the stress strain behavior for the ceramic we have already drawn, suppose this ceramic has been reinforced with particles. So, particles can also be ceramic particles only, but now the reinforcement has been done. Now, how it would be halved under loading? Let us see now how it will be halved? This is particle reinforced, so we have particulate reinforced. Also, we can say it is taking more stress as compared to the monolithic ceramic.

So, we have a monolithic ceramic stress strain behavior we have seen and we can see the stress that is required to fill ceramic material, which has been reinforced with particles is higher as compared to the monolithic ceramics. Now, let us take an another example in which the material or the ceramic matrix has been reinforced with continuous fibers. So, one continuous fibers are used as the reinforcement material in a ceramic matrix. How, the stress strain behavior would be we can see, so we can see that the failure is not sudden or catastrophic failure. The failure is non catastrophic type of failure, so his particular we can see graph is for fiber reinforced ceramic matrix.

So, we can see that a monolithic ceramic, how it is going to fail particulate reinforced? How it is going to fail and the fiber reinforced ceramic or a continuous fiber reinforced ceramic. How it is going to show the stress strain behavior? So, we have seen the stress strain behavior of three different types of ceramics that is monolithic ceramic particulate reinforced ceramic and continuous fiber reinforced ceramic. So, here we can see that there is certain percentage elongation in case of fiber reinforced, ceramic which improves the fracture toughness of the material.

So, this is one important point which we need to understand in case of the tensile and compressive behavior of the ceramic matrix composites. Now, let us see what are the other important mechanical properties that we should keep in mind. So, first important point we have seen tensile and compressive behavior. So, we have seen the when a

specimen is loaded, how it will behave in case of ceramic? How it will behave in particulate reinforced ceramic? How it will behave in the ceramic has been reinforced with continuous fibers?

So, that is one important point any particular combination of matrix and reinforcement, we are adding or blending together to make a ceramic matrix composite we should try to investigate experimentally. How it will behave under tension loading? How it will behave under compressive loading? So, that is one important point. Second important point is the fracture toughness. In case of ceramics it is one of the limitations, but when the ceramic is reinforced with the different types of reinforcement the fracture toughness improves.

So, we will see with the help of certain toughening mechanisms that how the toughening takes place or how the fracture toughness in case of reinforced ceramics is better as compared to the monolithic ceramic. So, we will try to address this point at a later stage, but one of the important points is that whenever we are combining the matrix or the ceramic matrix. The reinforcement together we should investigate that what is the improvement in the fracture toughness, which has taken place on the incorporation of the reinforcement.

Next is the important property of creep because we know that most of the ceramic matrix composites are developed for high temperature application. So, creep is a property which has three important points that is the time the temperature and the stress. So, all these combination of these they have to be taken into account when we are investigating that creep behavior of the ceramic matrix composites in certain cases because of the nature of the matrix and the nature of the reinforcement. We may not see much improvement in the creep behavior of the ceramic matrix composite, whereas in other cases we may see certain improvement in the creep behavior.

So, it is quite we can say ambiguous and it has to be investigated because the creep behavior of ceramic matrix composite would be depending upon two important criteria. That is the type of the matrix and the type of the reinforcement. So, we have to investigate that whether the creep behavior is improving or it is derogating by the addition of particular reinforcement in a specific ceramic matrix. Next important mechanical property is the fatigue resistance. Sometimes some of the products may be

loaded under cyclic type of loading, so under cyclic loading even if there is a minor crack or a flaw in the, we can say material or the product which has been made by ceramic matrix composite. There are chances that flaw or crack may further propagate under cyclic loading.

So, the behavior or the fatigue behavior of the ceramic matrix composite also has to be investigated. So, when the crack will propagate it may be getting addressed at a later stage because of the distribution of the reinforcement in the matrix, but we have to understand that how or what are the number of cycles to failure for a particular product, which has been made by the ceramic matrix composite? Finally, we have to understand the R curve behavior because this is slightly new term for in engineers. So, let us we can say just first try to understand that what is the R curve behavior?

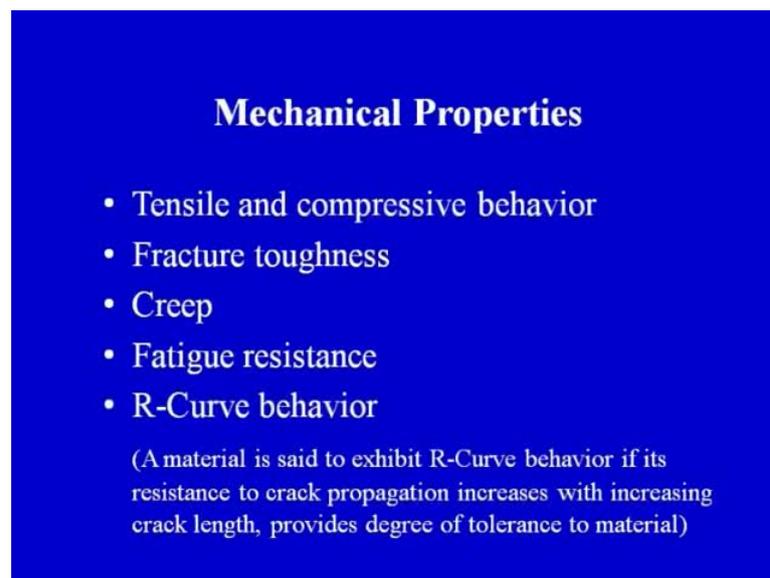
So, on your screen you can see a material is said to exhibit R curve behavior if its resistance to crack propagation increases there resistance to crack propagation increases with increasing crack length. So, this is the important point a material is said to exhibit R curve behavior if its resistance to crack propagation increases with increasing crack length. So, as the crack length is increasing the resistance to crack propagation is also increasing which means that it provides a degree of tolerance to material. So, if a particular material exhibits the R curve behavior, it means that it has the tendency to arrest the crack or to mitigate the effect of the crack and here are certain ceramic matrix composite materials, which exhibit the R curve behavior.

Therefore, they have the tendency to bridge the cracks. So, basically again I want to highlight that what do we mean by the R curve behavior because this is important in context of the reinforced composites. So, R curve behavior basically means a material is set to exhibit R curve behavior. If its resistance to crack propagation increases with the increasing crack length, so it provides better tolerance to the material or provide a degree of tolerance to the material. So, this is important in case of ceramic matrix composite because here we have incorporated the ceramic matrix with a reinforcement.

The reinforcement can be discontinuous fibers those can be viscose or there can be continuous fibers. So, basically the resistance to crack propagation may increase with the increase in the crack length in certain cases. In case of ceramic matrix composite it is not so that all kind of ceramic matrix composites will exhibit the R curve behavior, but there

can be few combinations of the ceramic matrix and the reinforcement which may exhibit the R curve behavior and these type of composites may be useful in certain applications where there are chances of failure under different types of loading. So, these are the important mechanical properties on your screen which we should always keep in mind, when we are propagating or when we are advocating the use of ceramic matrix composites for certain applications. Just to revise, we should investigate experimentally.

(Refer Slide Time: 33:20)



Mechanical Properties

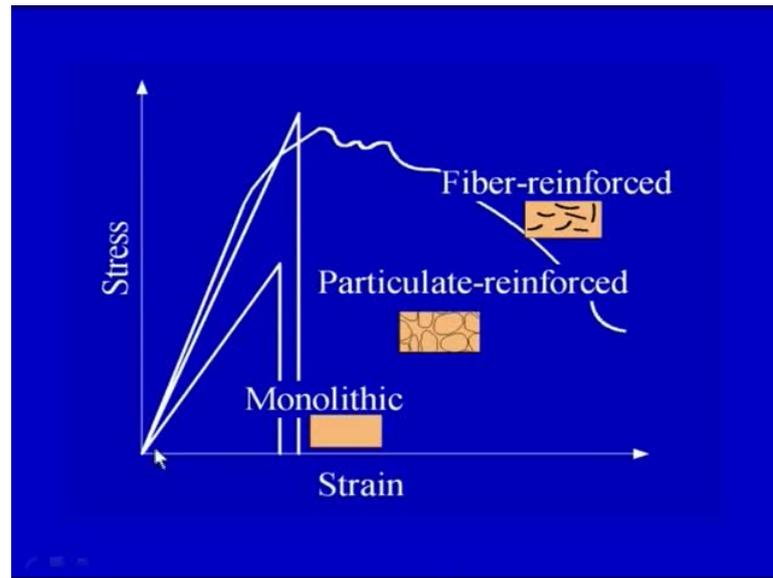
- Tensile and compressive behavior
- Fracture toughness
- Creep
- Fatigue resistance
- R-Curve behavior

(A material is said to exhibit R-Curve behavior if its resistance to crack propagation increases with increasing crack length, provides degree of tolerance to material)

The tensile and compressive behavior of the developed ceramic matrix composite, we should see the improvement in the fracture toughness on or on incorporation of reinforcements. We should the creep behavior, we should investigate the fatigue resistance property of the developed ceramic matrix composite. Finally, we should see that whether the material which we have developed whether the ceramic matrix composite exhibits the R curve behavior or not?

If it does not exhibit the R curve behavior, then necessary modifications have to be incorporated. So, that we are able to develop a ceramic matrix composite, which satisfies all the designed requirements. This is one important point or certain important properties we should always be taken into account. So, this is what we have already revise this is just a summary of what we have seen under stress strain behavior.

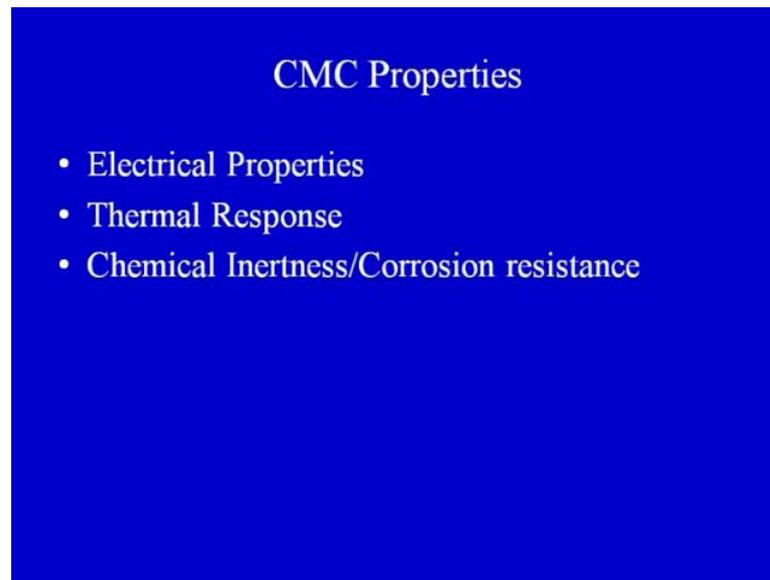
(Refer Slide Time: 34:19)



We can see of this is the monolithic ceramic no reinforcement is there, it is depicted by a clean rectangular bowl. This is only a ceramic material without any reinforcement this is a monolithic ceramic. Second one linearly goes here and then it has a failures sudden failure. It is a particulate reinforced in which there are small particles of reinforcement in the ceramic matrix. So, this is particulate reinforced ceramic matrix composite this particular sudden failure is taking place. Finally, this is non-linear behavior shown here.

Then there is a failure taking place, but it is not a catastrophic failure. It is there is certain percentage of elongation before final rupture or final failure, so this is fiber reinforced in which we have short fiber even in case of fibers also. We may have this type of behavior only, so this is fiber reinforced in which we can have continuous fiber or fibers will certain length, So, fiber reinforced ceramic matrix composite will show a different stress strain behavior on loading particulate reinforced will show a different type of behavior. The monolithic ceramic will show a different type of behavior under mechanical loading. So, here we are trying to compare the stress strain behavior on loading of the monolithic ceramic, the particulate reinforced ceramic matrix composite and the fiber reinforced or the continuous fiber reinforced ceramic matrix composite.

(Refer Slide Time: 35:59)



Other properties that should always be kept in mind, apart from the mechanical properties of ceramic matrix composites are the electrical properties. If you remember in our lecture number 1 we have seen that the thermal conductivity of ceramics is lower as compared to metals. Therefore, the ceramics can be used for electrical insulation purposes. So, they are used also for electrical insulation purposes, so in case of CMCs also we can tend to have certain properties, where they can be put forward for applications where electrical insulation is required.

Similarly, thermal response of CMCs also have to be investigated that are elevated temperature, when a CMC or a ceramic matrix composite product is been used, whether it would be able to retain its hardness or its strength or it will have certain thermal cracking or thermal stresses that would develop, which may further lead to the failure of the ceramic matrix composite product.

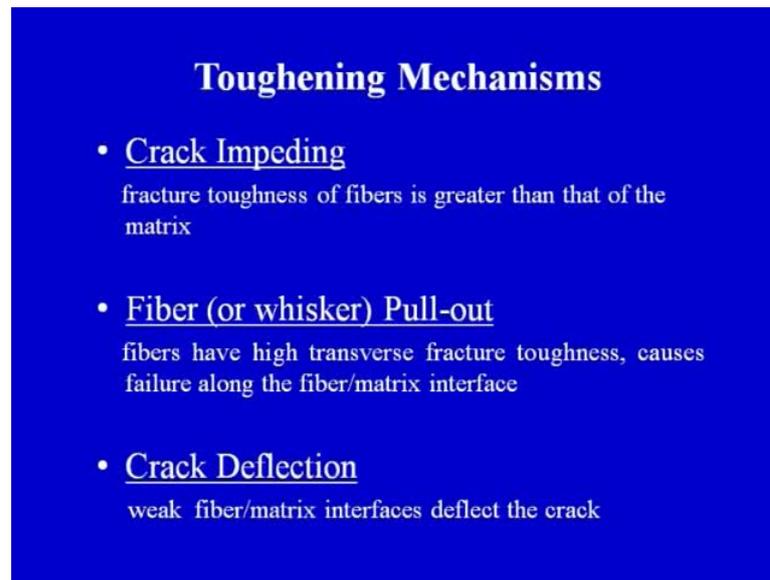
So, basically what has to be addressed here is that apart from the mechanical properties of ceramic matrix composite, where we have seen the most of the properties are improving on incorporation of the fibers. We have to also look into the other properties such as the electrical properties, the thermal properties as well as the chemical inertness and the corrosion resistance because in certain applications like chemical inertness of ceramic matrix composite is also important.

So, the point of highlighting these important properties that apart from the mechanical properties as an engineer we should also try to look into the electrical thermal and chemical properties of ceramic matrix composite. So, because we are focusing on the fundamental aspects of ceramic matrix composite, we cannot go into the detail of each and every property, but on an average or on in, on an in a in a general manner. We can see that CMCs also tend to be electrically insulation or electrically insulators because the bulk of the material is a ceramic material and the reinforcements also.

In many cases would be ceramic material only and there would be certain types of pores and flaws and certain inclusions also in the ceramic matrix composite, which tend to make them the electrically insulating material. So, CMCs in most of the cases would be electrically insulating thermally also. We need to look into thermal aspects because one of the important properties is a property of a hot hardness which means the CMCs have the property to retain their hardness at elevated temperature. So, that thermal response of CMCs at elevated temperatures also needs to be investigated.

If a particular combinations shows the property of hot hardness like combination, I mean to say the combination of the matrix and the reinforcement shows the property of hot hardness. Then it is suitable for elevated temperature applications. Finally, the chemical inertness and corrosion resistance the ceramics have the property of chemical inertness and corrosion resistance. Therefore, ceramic matrix composite also should have the property of chemical inertness and corrosion resistance. So, these are few properties which have to be taken into account before we design a product, which is going to use the ceramic matrix composite as the material. So, basically till now we have seen that what are the important properties in context of ceramic matrix composite, which have to be looked into...

(Refer Slide Time: 39:49)



Toughening Mechanisms

- Crack Impeding
fracture toughness of fibers is greater than that of the matrix
- Fiber (or whisker) Pull-out
fibers have high transverse fracture toughness, causes failure along the fiber/matrix interface
- Crack Deflection
weak fiber/matrix interfaces deflect the crack

Now, let us look at the toughening mechanisms because we have seen that the fracture toughness of the ceramic matrix composites is higher or better as compared to the monolithic ceramic. So, what are the various types of toughening mechanisms in picture? So, let us see three important toughening mechanisms. So, if you move on to just have an idea that why toughening is taking place because in case of ceramics we have no reinforcement. In case of ceramic matrix composite we have an additional reinforcing phase.

So, basically in ceramic matrix we have added some additional phase or are reinforcing phase, which can be in terms of particles or fibers. So, one important toughening mechanism is the incorporation of fibers in the ceramic matrix is that of crack impeding. So, crack impeding means the arrest of the crack or we can say crack arresting. How does crack arresting take place? Why does crack arresting take place because the fracture toughness of fibers is greater than that of the matrix. So, fibers that we are incorporating as the reinforcement in the ceramic matrix have higher fracture toughness as compared to the matrix.

Matrix is the ceramic material, so basically just to remember we can say that the properties of the fibers are better as compared to that of the matrix or the load bearing capacity or the fracture toughness of the reinforcement is better or higher as compared to the matrix material. Therefore, they have the crack may propagate in the matrix, but it

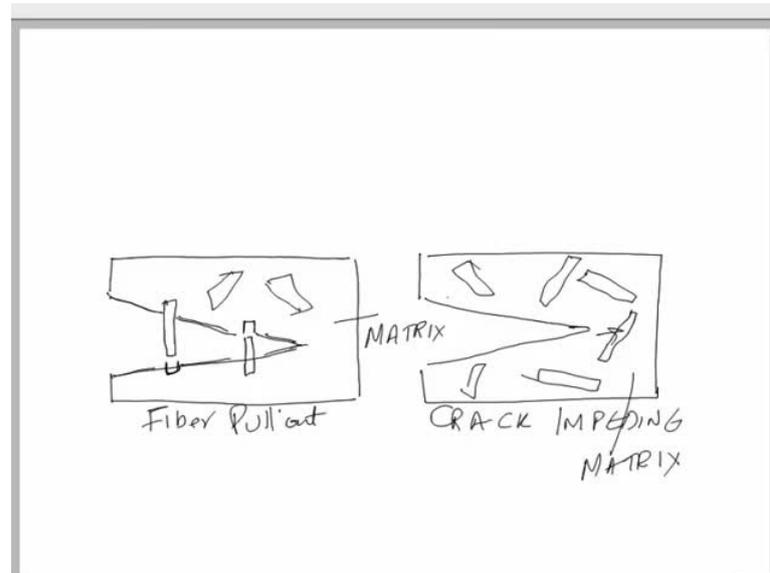
may not be able to tear open or it may not be able to crack or the crack may not be able to propagate through the fibers. So, it may not be able to tear open the fiber because the fiber has higher fracture toughness of as compared to the matrix. So, that is one of the important points that is crack impeding that is crack will get arrested whenever it will hit a fiber.

Why the fiber will be able to impede the crack or it would be able to arrest the crack? Because the fracture toughness of fibers is greater than that of the matrix. So, first toughening mechanism is the crack impeding mechanism, next is the fiber or the whisker pull out. So, there reinforcement can be in terms of fiber or it can be in terms of viscose it will be pulled out of the matrix. So, fibers have high transverse fracture toughness it causes failure along the fiber matrix interface, so basically the failure. Now, will tend to at the fiber matrix interface and the fibers will be able would be coming out of the matrix and they will not allow a catastrophic failure of the ceramic matrix composite to take place.

So, these are some of the mechanisms that take place when the crack travels through the ceramic matrix composite. So, when the crack will travel through the ceramic matrix composite first toughening mechanism may take place. It may hit a fiber and may and may get arrested there. Second is it may not hit a fiber, it may hit a fiber and the it has the energy the energy may be released at the by failure at the matrix. The fiber interface or the fiber matrix interface and the fiber may pulled out of the matrix and the failure may takes place at the fiber matrix interface.

But it will not be a catastrophic failure and the last one is the crack deflection. So, crack when it is moving it may get impeded it may get we can say it may released its energy by the opening for the fiber pull out or finally, the crack deflection may take place weak fiber matrix interface deflects the crack. So the deflection deflection of the crack may also take place. Now, let us try to understand these toughening mechanisms with the help of the diagrams because just by reading on the slide the things may not be that clear. Now, let us try to understand them with the help of a diagram.

(Refer Slide Time: 44:07)

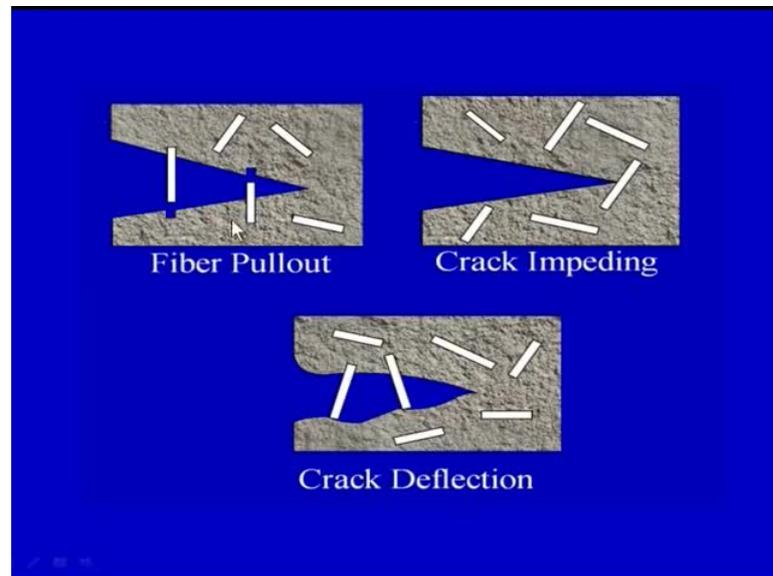


Now, on your screen you can see suppose this is the matrix material. So, what is this? This is matrix and this is the crack which is propagating and these are the fibers. So, this fiber might have been pulled out of here this is another fiber, we can say which has been pulled out from here. So, the fiber pull out has taken place there can be other fibers also other fibers which are the reinforcing phase. So, this is basically a fiber pull out, so the fiber is getting pulled out and the crack is getting arrested or it may travel along the fiber matrix interface and in another case we can see again we have a matrix material.

So, here we can see again this is a matrix and in this matrix we have different types of fibers and one of the fibers we can say is at this point and here we can see the crack, when it will move and it will hit this fiber. It will get impeded or arrested, so this particular toughening mechanism is called the crack impeding. So, we can arrest the crack with the help of the we can say fibers which we have incorporated into the ceramic matrix.

So, two important we can say we have seen the toughening mechanism, that the fiber pull out fiber will pull out. It would try tend to arrest the crack or bridge the crack and the crack would then travel along the fiber matrix interface. Finally, it will get arrested and crack impeding fiber may arrest the crack because the fibers have higher fracture toughness as compared to the ceramic matrix. So, let us see the diagram which we have for this particular toughening mechanisms.

(Refer Slide Time: 47:09)



So, on your screen you can see, again these are the diagrams on your screen. This we can see this is the fiber pull out which has taken place fiber pull out, then crack impeding this is the crack which is propagating in the matrix and it will get arrested or impeded here. So, crack impeding toughening mechanism fiber pull out toughening mechanism and the crack deflection because of the fiber the cracks may also. So, sometimes get deflected and the resulting failure will not be a catastrophic failure where as in case of ceramics we will have a catastrophic failure.

So, one important point that we can high light here is that by the incorporation of fibers here we have we can say this continuous type of fiber randomly oriented fibers and in case of continuous fibers also the toughening mechanism would be in auctioned. So, we can have continuous fiber reinforcement, we can have discontinuous fiber reinforcement, we can have randomly oriented reinforcement, we can have aligned reinforcement, but in all cases because of the incorporation of the reinforcement into the ceramic matrix.

The toughness stands to improve and these are certain toughening mechanisms which are in action. So, with this come to the end of today's discussion. Although we have to discuss certain important points, but because of the time limitation will break here and we will start our discussion regarding the processing and the secondary processing of ceramic matrix composite in the subsequent lecture. We will also try to see that what are

the limitation or the major challenges that why the ceramic matrix composites are not finding many applications in engineering?

So, with the we can say discussion of the basic aspects and properties of ceramic matrix composite will come to an end today. We will start our discussion with the basic challenges for ceramic matrix composites the processing techniques for ceramic matrix composites, thus why the need why there is a need for secondary processing for ceramic matrix composites? Finally, we will start with one of the processing techniques for ceramic matrix composites.

Thank you.