Processing of Polymers and Polymer Composites

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Lecture - 29
Joining of Polymer Composites

In the last session, if you remember we started our discussion on a very important aspect in processing of polymer based composites. Not only in processing of polymer based composites, but also in secondary processing of polymer based composites. We have focused on the introductory part of the secondary processing as I think I have explained number of times earlier also that processing of composite materials can broadly be classified into 2 important categories. First one is primary processing of polymer composites and then, the secondary processing in primary processing. We process a part. For example, this pointer, the whole body has to be made. We will use any moulding technique to make this body in secondary processing. We have to do some machining or cutting or fitting or assembly that will fall under the secondary processing.

In our previous session, we have just started the introductory part of secondary processing. That is why secondary processing of polymers as well as polymer based composites is required and it is an important aspect. Why because it is easy to make a moulded product, but it is very difficult to assemble it to make a complete product assembly. If the shape of the final product is very complicated and if you remember in the previous class or previous session we have seen and I have given this example of the assembly of an aircraft.

Now, aircraft has lot of polymer composites and I think in one of our previous sessions, we must have seen a diagram or a figure depicting the aircraft parts that can be made by composite materials or if we have not seen that figure very easily, you can Google it and you will be able to find out the number of parts that are made out of composite materials which are used in the aircraft for its final assembly.

Now, it is easy to make these parts using any standard process for polymers or polymer composites or plastics or fiber reinforced plastics. You can use compression moulding, you can use injection moulding you can use rotational moulding, you can use filament winding, you can use pultrusion. So, there are number of processes well developed for

plastics and plastic based composites, but when these parts have to be assembled to a main assembly or assembled to the main frame, it requires lot of thinking, lot of challenges are there and therefore, we need to understand that what are the secondary processing techniques that is, what are the secondary techniques or assembly techniques or joining techniques or machining techniques that can be employed for these polymer based composites as well as for polymers.

Today as you see on your screen, our target is to understand the basic philosophy, the basic thought behind the joining of polymer composites. In the last session, we have seen a long list of processes which are used for secondary processing of composite material, but today our focus would be on the joining of polymer composites and we will be seeing that what are the major category of processes which can be used for joining of polymer composites. So, joining as we all understand that there are 2 different parts. Suppose these are 2 different parts and we have to join them together like this or we have to join them together like this or in any other joint configuration we have to choose a process which will be able to provide as a good joint. Good joint means that it has good bond strength between the 2 adherents.

It do not fail on loading, it do not fail under in service conditions. So, we have to see that what are the processes that are used for joining the polymer based composite materials, so that we get a good assembly, we got a good joint and right joint does not fail when it is put into use or when it is put into practice. So, we will try to understand today that what are the broad classification of processes that are used for processing of polymer parts more specifically secondary processing of polymer parts and to be even more specific for joining of the polymer composites or polymer parts. So, let us start our discussion with a very introductory slide which gives us the need of joining that why do we need to join the parts together.

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In the last session also, we have seen the need of joining. Today again we are revising, we are reemphasising, we are highlighting, we are outlining the reasons required for joining the polymer based parts. First as I have already explained to fabricate large and intricate composite products if there is a very large size product, we can make it using primary manufacturing process also, but for usage purposes, we may require some secondary processing may be cutting of a window or cutting of a manhole or cutting of maybe a particular section to just fit in some window, with window in that particular section maybe there can be other rolls where we have to machine a specific part in order to assembly, for assembly of the nut and bolt.

So, joining is a indispensable operation for any manufacturing process or for any manufacturing cycle. Not only for polymer composites, I think joining is an important aspect, important step in product development in metals also. We see lot of literature, lot of good books written on welding, soldering, brazing. So, there are processes which are well developed for joining of metals, but for joining of plastics, usually it is not covered in the undergraduate curriculum and the information is also limited. So, today we will try to see that what are the processes that can be used for joining of polymer composites. Why a joining is required? It is because when we have to make a large assembly or a large structure or a complicated structure or a complex or intricate geometry of a structure, there we require joining operations and first point that is outlined in this slide is that joining is required to fabricate large and intricate composite products to the

individual components or parts. May be composite means may be made up of a composite material or may be made up of a metal also or may be made up of a thin sheet of metal also, but when these have to be combined with a composite part, we have to see that how the 2 adherents or the 2 members or the 2 sub-assemblies can be joined together.

So, first and foremost we need to understand for making complex products, we require joining operations and joining of metal to polymer or polymer to ceramic and all these joining strategies require lot of attention because it is a difficult or a cumbersome task. It is not impossible, but it is difficult to create relative motion between the meeting parts. Sometimes we may require a motion between the 2 parts. So, it cannot be made in single part. Therefore, we may require the joining of the 2 parts, maybe one section is this and another section has to swell around this section. So, we require joining at this point, so that the 2 sections can move relative to each other. The third point on your screen is proper load distribution and transfer. So, there also we require the joining of 2 or 3 or 5 or 7 different parts to provide maintenance repair and service.

In many cases, you will see for regular maintenance, for preventive maintenance, for scheduled maintenance, we need to open the different parts. For example, the camera that is recording this session, the camera is made up of so many different parts. Now, for scheduled maintenance maybe after 2 months, we may require to open the different parts, clean them and then, fix them again together. So, they have to be joined in such a way, so that they are easy to disassemble and easy to assemble and for maintenance purposes, it is always advisable that we make it in so many number of parts, so that very easily we can disengage them, do the cleaning, do the maintenance and then assemble them together. So, joining is required to provide or to assist in the maintenance repair and service of the product.

So, joining has got lot of advantages and therefore, we need to understand that what are the challenges in the joining of polymers and polymer based composites. We are usually focusing today on composites or polymer based composites. Joining techniques can broadly classified into 3 major classifications or 3 major broad areas. First one is the adhesive joining, the most commonly used technique for joining of polymers as well as for polymer based composite.

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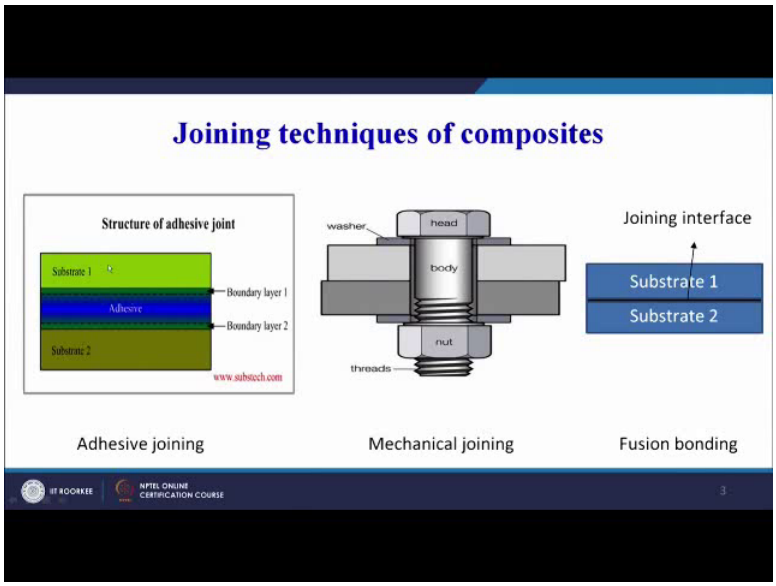

So, we can see here we are calling it as a adherent. This is adherent or substrate 1. You can call it a substrate also. So, substrate or adherent 1, this is substrate or adherent 2 and this is the adhesive, blue colour adhesive applied between the two. Now, this is just to explain that how joining can be done using an adhesive.

If you remember in one of our previous sessions, we have also seen the joining. I think in the previous session only where 2 glass substrates or adherents were joined together with the application of an adhesive which was a kind of liquid gel which was applied on one of the adherents. The another adherent was placed on top of it and then, a heat was supplied with the help of a lamp. So, this is similar type of joining. There are 2 adherents, in between there is an adhesive and must I say that adhesive layer will not be as thick as the substrates, but this is just for depiction or just for explaining that there is an adhesive layer between the 2 adherents and that is very very important.

Now, another important point to look at this stage is that there is a boundary layer here. You can see on the screen, this is a boundary layer. The boundary layer is there between the substrate 1 or the adherent 1 and the adhesive and there is boundary layer 2 between the adherent 2 and the adhesive and these are the 2 zones which are very prone or most prone to failure. When we apply load on this type of a adhesive joint, there is a tendency, there are 3 types of failure may take place. Now, some of you may be wondering that how 3 types of failure can take place.

Now, the first type of failure that can take place is the failure of the substrate itself. How that can happen? That can only happen if the joint strength is very high that is the adhesive and the adherent are having very high joint strength failure of the adherent may take place. That is first type of failure. Second type of failure can be the failure of the adhesive. So, the joint strength between the adherent and the adhesive is very good. So, the boundary layer 1 is intact and boundary layer 2 is intact, but the adhesive has failed form in between or the bulk failure of the adhesive has taken place second type of failure. What can be the third type of failure?

Now, the third type of failure as you have rightly guessed is the failure between the adhesive and the adherent. That is the failure at the interface between the adhesive and the adherent. It can be at boundary layer 1; it can be at boundary layer 2. So, adhesive joint can basically fail in 3 ways. First way is bulk failure of the adherent. In case of composites, if it is a laminated composite, so the adherent is a four layer laminate. Adherent 2 is also four layered laminate. So, the failure of the adherent, maybe the delamination of the four layers from the bond, so 2 layers may get delaminated on application of load, but the joint is intact.

So, that is the bulk failure of the adherent. Second is bulk failure of the adhesive and third is the failure at the joint that is at either at boundary layer 1 or at boundary layer 2. That maybe the debonding between the adherent and the adhesive. So, debonding may take place between the adherent and the adhesives and that is also one of the most common types of failure. So, 3 major failure modes, failure types can be observed in case of the adhesive joints.

Now, we come to the mechanical joining. In mechanical joining, we see that there is an additional element that is a nut, this is the nut and there is a head and this is the body. So, we have a nut and a bolt type of assembly. So, we have 2 adherents here. These are the adherent, this is a adherent. One light grey colour adherent, 2 dark grey colour and this is the body nut and bolt type of assembly and these are the washers on top and the bottom.

So, we can have a mechanical joining or mechanical fastening of the composite parts also. Now, the major challenge in case of mechanical fastening is that we are using composite materials, specifically if you remember for lightweight applications, but when we use the nut and bolt type of assembly, it is very difficult to make composites. The

bolts and nuts of the composite material with the threads, it is easy for plastic or polymer parts, we can make, but for composite it is slightly difficult. So, majorly the nuts and bolts that are used are made up of metals only and for metallic fasteners, they will definitely add weight to our composite structure.

So, the use of mechanical fastening is also maybe a challenging task because it will add weight to our overall assembly. The second major limitation in case of mechanical fasting is the holes that are required for facilitating the joining operation or the fastening operation. So, making of holes in composite parts is a very very challenging task and we will cover it in our subsequent session that in composites what are the challenges in making holes and how they can be overcome or partially they can be overcome. So, we have seen the types of failure in case of adhesive joining.

The types of failure that may occur in mechanical joining because when we make a hole in a composite part, there will be some damage that we call as the drilling induce damage around the hole and that may lead to the failure of the joint. When it will be loaded under different types of mechanical loading environment, then the last part or the third type of joining is the fusion bonding. In fusion bonding, there is a joining interface between the substrate 1 and the substrate 2. So, this is also one of the important techniques where there will be a different source of heat which will the 2 substrates or 2 adherents together. Now, here also there are challenges that we need to only focus as the interface area we have to do the masking of the other sections or the other part of the adherent. Why?

It is because when we are supplying heat, we want to expose only the joint interface area to the heat. We do not want the other portion or the other section or the other bulk of the adherent to be exposed to that heat and that is also one of the challenges.

Then, the joining may sometimes require additional maybe sub additional substrate or may be inside the 2 substrates. So, it can be additional member may be required inside the 2 substrates in order to facilitate the joining. We will see in our subsequent slide. So, basically these are the 3 important joining strategies that can be adopted for joining of polymer based composites and similar type of techniques can be adopted for joining of polymers also. So, we will see each one of them are slightly, try to understand that what are the challenges. I think I have explained the challenges alongside the techniques also,

but further we will try to understand that what is the importance of each one of these techniques in joining of the polymer composites.

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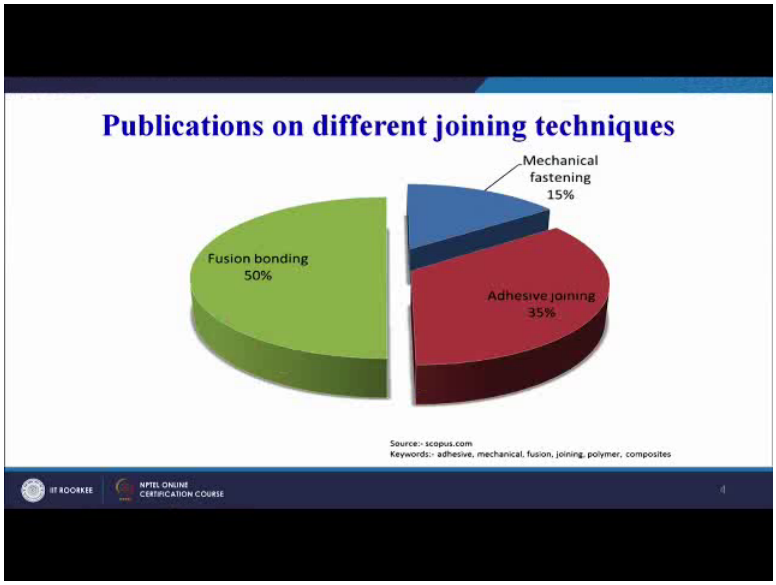

Just let us try to understand the state of the art or state of the research which has been conducted in these joining techniques because this is something which is a latest advancement in the field of joining of polymer composites because earlier major parts were made by the primary processes only and they were used, they were made to a near net shape, but now when the complexity of the products has increased, the application spectrum of the polymer composites has widened.

Therefore, the need of joining different parts together has been realised and lot of people all across the world are putting research efforts to develop newer and newer method of joining them successfully and this slide on your screen is highlighting the publications that is the research articles or the research summaries or the white papers published on the different joining techniques. So, you can see approximately 50 percent focus is on fusion bonding. So, if a researcher or an engineer has to look that which technique will be most suitable, if all 3 are possible because for an adherent, all 3 techniques may be possible, fusion bonding may be possible, mechanical joining will be possible as well as the adhesive joining may be possible.

So, we add an engineer has to take a decision that which particular process he should choose or which particular joining methodology or joining strategy he should adopt, but

from research point of view people have focused more on fusion bonding may be approximately 50 percent adhesive joining 35 percent and for mechanical fastening only 15 percent articles have been reported.

Now, some of you may be wondering; what is the source of this data. Your source of the data is Scopus which is a database which has lot of literature, lot of research articles available online and there if you put the keywords such as adhesive joining, mechanical fastening joining of polymer composites, we will get lot of articles and then, you can do the analysis and find out the relative importance of each and every technique. So, we can very safely conclude from this slide that major focus of researchers is on fusion bonding. Now, this is giving a global summary of joining if you see again the sources Scopus only. So, this is India, United States and Germany on joining of polymer matrix composites.

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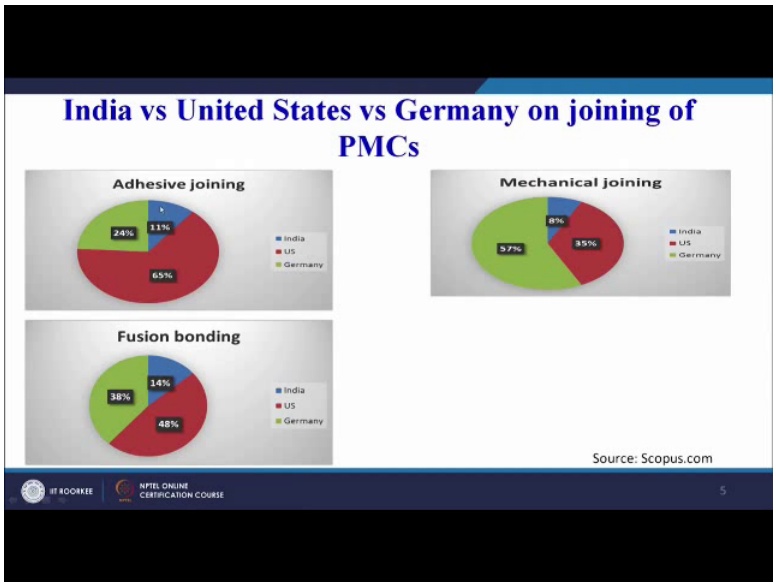

So, we can see from joining point of view, blue colour is India. 11 percent focus is there. 14 percent in case of fusion bonding and only 8 percent in case of mechanical fastening and the green colour is Germany and the red colour is United States. So, we can see that in India, we are not focusing that much on the joining aspects of polymers as well as polymer based composites and therefore, we need to pick up and we need to investigate, we need to examine, we need to analyse, we need to experimentally find out and develop newer and newer methods of joining of polymers as well as polymer based composites because we have to see the product reaches to the customer with a particular quality.

If the individual components and parts are very very good, but the joining is not proper the product may fail and may not be able to deliver the function for which the product has been designed there for joining has got lot of importance and here we can see from this slide that our efforts are not being reflected at the word stage and therefore, we need to fill up, we need to see that we also develop some newer and newer methods for joining of polymers as well as polymer based composites.

Now, let us try to understand all these 3 processes one by one. Now, since the major focus is on fusion bonding, let us see that what is the basic joining mechanism. I am not going to do too much of the micro level explanation, but broadly I will try to highlight that how the fusion bonding take place. Now, in fusion bonding if you see in the diagram, there is substrate 1 and there is a substrate 2 and this is the overlap area, this is the overlap area and this overlap area what we have to do, we have to expose it to heat. So, when we expose this overlap area to heat, what happens inside the adherent that we will try to understand with the help of a few chains or whatever the polymer chains which are there at the interface. So, fusion bonding is mainly applicable for joining of thermoplastic composites.

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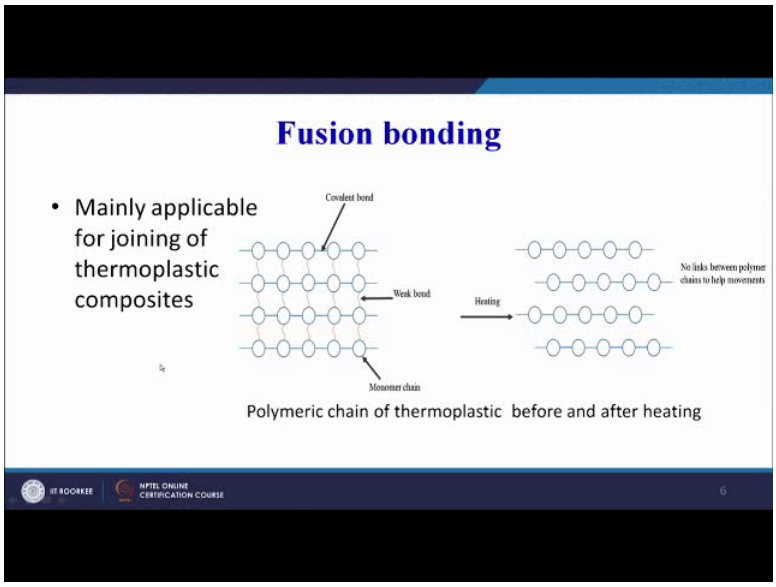

So, this is the first classification. If you see in the very beginning, we have seen that polymers can be either thermoplastic or they can be thermo sets. So, fusion bonding majorly is applied for thermoplastic type of composites and since it is applied for

thermoplastics, you can see there are long chains bonded by covalent bonds inside. So, there you can see these are long chains that there are weak bonds here. These are the covalent bonds here. Now, this is the monomer chain which is shown here. So, this is a monomer and this is a polymer chain. So, we can see the polymeric chain of thermoplastic before and after heating. So, this is before heating there are weak bonds inside, but when you heat, the weak bonds disappeared and only the covalent bonds exists. So, no links between polymer chains and this helps movement and when they will move, they will slide. Reorientation will take place and the bonding may happen between the 2 substrates.

So, in fusion bonding, this is suppose the top of substrates, this is the bottom substrate at the join interface. When you will supply heat, this type of situation will develop that the weak bonds between the polymer chains will disappear and there will be sliding of the chains and that will lead to reorientation and joining of the 2 composite parts. So, that is very fundamental, very basic explanation of why the joining takes place when you supply heat at the joint interface. This is again another explanation.

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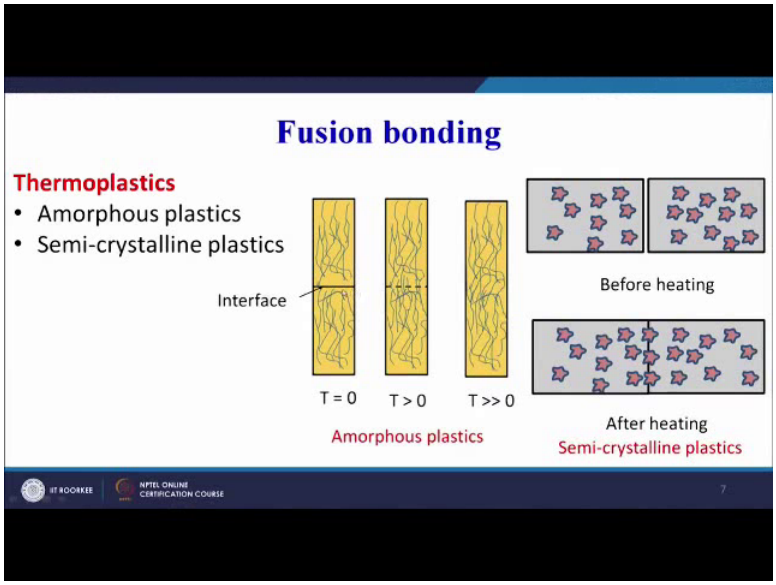

Here you can see this is the interface where joining has to take place or joining has to happen. So, we can say amorphous plastics, we can have semi-crystalline plastics, we have seen in our initial sessions on polymers. We have seen that polymers can either be thermo sets, they can be the thermoplastic, they can be amorphous, they can be

crystalline, semi-crystalline. So, we have seen that explanation in the very beginning. So, amorphous plastics and semi-crystalline plastic, this is showing how the joining will happen between the amorphous plastics.

This is T0 and that is there is no heat being supplied. This is one adherent or substrates, this is another adherent or substrate, then when the T is or heat is given or temperature is increased, this transition takes place and this interface weakens and when the T is further increased, there is a long chain formed, long polymer chains are formed and they joined or the joining at that interface takes place. Similarly for semi-crystalline plastic also, there are 2 adherents or 2 substrate.

This is before heating condition, but when you heat, the bonding takes place and we get a semi-crystalline plastic joint. So, we have a joint interface here where we can see the joining has taken place and here also at this interface, the joining has taken place. I think the explanation here is not absolutely clear as it should have been for the learners, but the next slide we will make it very clear that how joint takes place or what are the bonding mechanisms that happen.

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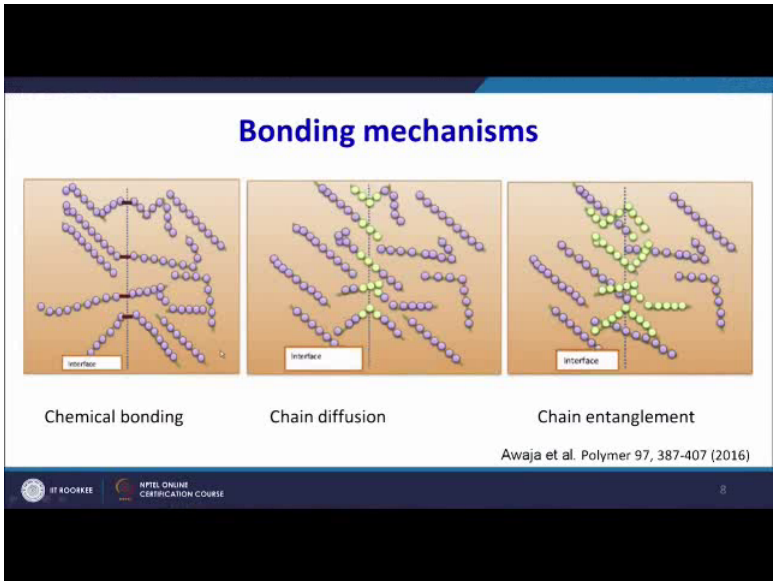

So, when there are this is the interface as in the previous slide, there was a interface and the chains were getting entangled or the polymer chains was sliding against each other at the joint and then, they were forming a bond, but here you can see very clearly that how this bonding can take place. This is the interface, this is the interface and at this interface

the chemical bonding takes place. This dark brown colour bonds represent the chemical bonding between the polymeric chains. So, these are the polymeric chains. So, the polymeric chain of one substrate or adherent are forming a chemical bond with the polymer chain of the other adherent and therefore, the bonding is taking place and the joining at this interface will happen. Similarly, chain diffusion is other bonding mechanism here. We can see this is the diffusion of the chain across the interface here, across the interface chemical bonding has taken place here, across the interface the diffusion has taken place.

The chain diffusion here we can see and this diffusion of chains, we will also form the joint between the 2 adherent or the substrates and third one is the chain entanglement. Here we can see the chains will get entangled with each other and therefore, forming the joint you know some of you may be wondering that how that is true. There are 2 different polymeric adherents or polymer composite adherent. We are bringing them together and there is a interface between the two. We are supplying heat. Now, how the joint will take place. This is explaining the bonding mechanisms and it may so happen that only chemical reaction or only chain diffusion may not happen. There may be a combination of the boning mechanisms that may happen depending upon the type of the adherents we have chosen. If both adherents are of same type of material, we may get a different type of bonding mechanism or may observe a different type of bonding mechanism. If the 2 adherents are of different materials, we may get a different combination of bonding mechanisms, but fundamental bonding mechanisms will remain same. That is the chain diffusion, chain entanglement and the first one that is the chemical bonding.

So, any one of these or combination of 2 or combination of 3 may happen depending upon the specific requirements, but these are the 3 major mechanisms which are used and if you see the source, the source is a research article published by Awaza in polymer. That is the journal name and the article is only 1 year old. It is 2016 article. So, that means whatever we are discussing is the latest in the field of joining of the polymers and polymer composites and it can be challenged also. This may be reported by one of the researcher, but as learners we need to understand what is the latest that has been reported and how the joints are formed for the polymers and polymer composites.

These are the 3 bonding mechanisms reported by the latest research in the field of co-joining of polymers.

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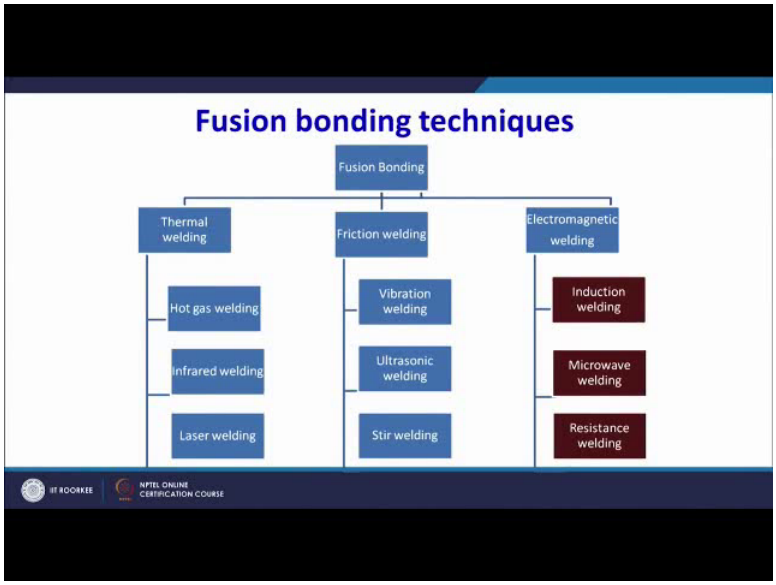

Now, fusion bonding techniques we can see. In fusion bonding, broadly they can be classified into 3. First one is the thermal welding friction, welding as well as electromagnetic welding. Now, you can see in all where the word welding is coming from. Now, the basic definition of welding is the joining of 2 similar or dissimilar materials with the application of heat, with or without the application of pressure. So, we will see that one parameter is constant that is application of heat and whenever the 2 adherents have to be joined together, we have to supply some amount of heat and that heat can be from a hot gas. It can be from infrared source; it can be from a laser source.

Similarly, we can have heat from vibration, we can have heat from ultrasonic, we can have heat from stirring of the material. Similarly, we can have heat from induction welding, we can have heat from microwaves, we can have heat from resistance. So, our focus primarily be on the electromagnetic welding which is one of the cleanest source of joining the 2 different materials together or 2 different polymers or polymer based composites together. Now, in induction joining very quickly will try to understand the basic mechanism.

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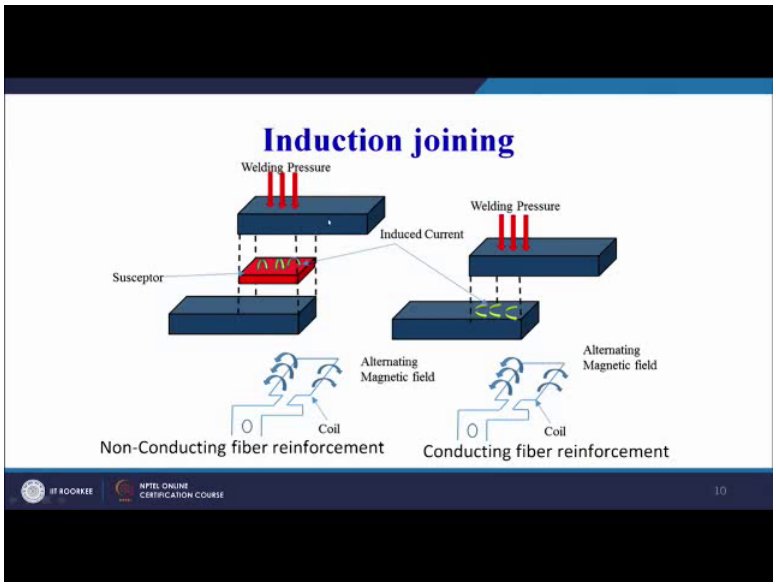

So, in induction joining, this blue adherent and this blue adherent have to be joined together and this is a specific case in which the non-conducting fiber reinforcement is there. Now, for any polymer composite, you know that reinforcement will be in term of the fiber and the bulk will be in terms of the matrix or the polymer. So, if your fibrous reinforcements is non conducting, so for non-conducting we have to put a susceptor inside which will be a conducting material. This red colour susceptor will help to conduct or current and thereby form the joint. So, this is for a non-conducting fiber reinforcement. Contrary to that if we have conducting fiber reinforcement that may be it can be a carbon fiber, then we can say that no need of a susceptor or another additional material.

We will directly apply the current and both the adherents will be brought together and it will help us in joining due to the induction heating effect. This is the microwave joining in. We use microwave oven in houses. Very quickly I will try to explain this.

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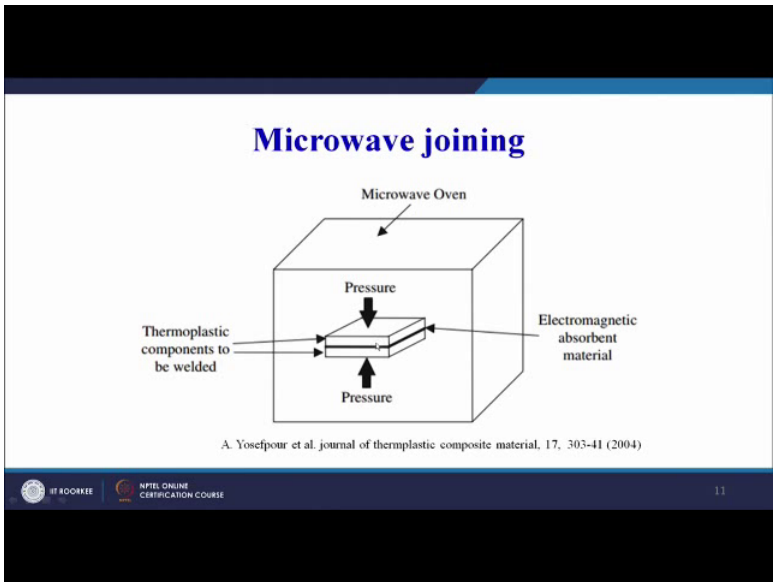

These are the 2 we can say adherent thermoplastic components. Well, this is our first component. Second component in between we have put this black solid line depicts the electromagnetic absorbent material which will absorb the electromagnetic waves or the microwaves and when pressure will be applied because of the heating effect induced by the electromagnetic absorbent material, there will be adjoint that will be developed between the 2 thermoplastic composite materials.

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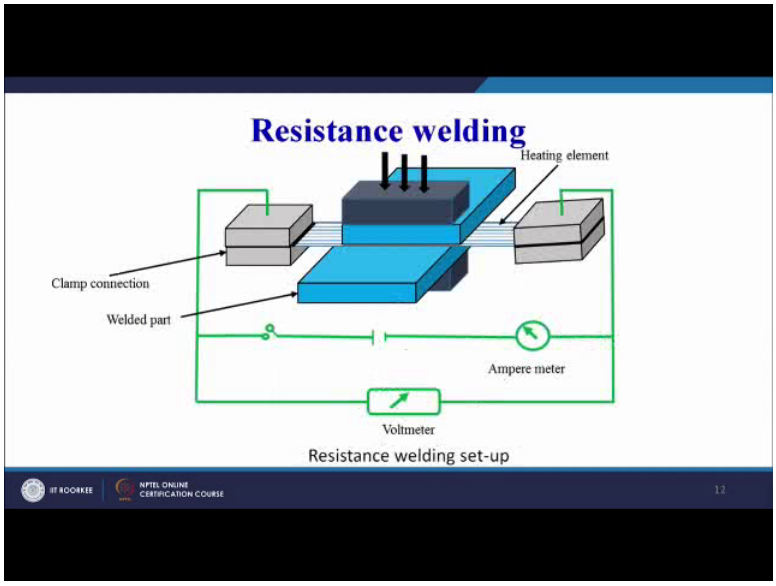

The last one that is the resistance welding. Here we will see this is a coil heating element. These lines depict the heating element, the sky blue colour 2 material or 2 composite parts that we want to join together that is welded parts or the parts to be welded and then, we apply pressure from top and then, once the current flows between the 2 adherents, we can join the 2 parts together because of the heat. So, I have already told that whenever we have to join the 2 polymer or the polymer composites part together, we have to supply heat that is mandatory. In addition we may apply a pressure; we may not apply pressure.

So, today we have seen 3 important techniques that can be used for joining of polymer composites. The first one is the fusion bonding, the second one is the microwave joining, the third one is the resistance welding, but these processes as I have said are easier to explain, but they are very difficult to control and there are number of factors which influence the fusion bonded joints.

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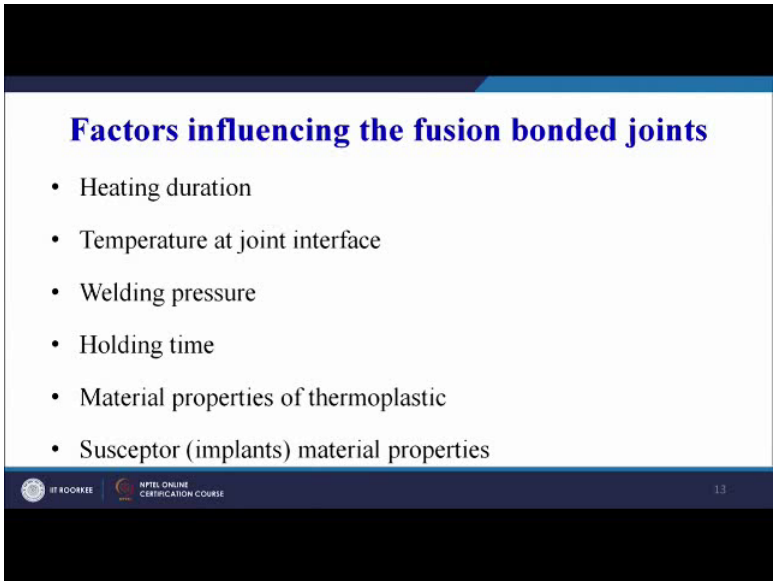

Now, these can be the heating duration the temperature at the joint interface welding pressure holding time material properties of a thermoplastic as well as a susceptor or the implant that we that we put inside the 2 adherents. So, each one of these require further discussion, but today as we have to wind up our session because it is an half an hour session, we will discuss each one of this process in further detail and try to understand each and every process that what are the limiting factors, what are the advantages, what

are the application areas for each one of these process because these are the 3 important processes which are used for joining of polymers as well as polymer based composites.

In our subsequent sessions, we will discuss each one of them in one session and try to further understand the mechanism, the advantages, the limitations as well as the application areas of each one of this process. With this we conclude today’s session.

Thank you very much.