

## **Manufacturing of turbines (gas, steam, hydro and wind)**

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**Week - 07**

**Lecture 33**

Welcome to this course on manufacturing of turbines. So, in this lesson 33 of the course, we will see details about the manufacturing of the wind turbines using various manufacturing processes. Specifically in this lesson, we will be focusing on hand layup and spray layup process. So, the outline of this lesson will be as follows where, first we will discuss the introduction to the various manufacturing techniques for the wind turbines. We will look at the various manufacturing techniques and their classification. We will also look at details on various factors which need to be considered while making selection for an appropriate manufacturing process.

So, in this regard, we will see details about degree of cure, viscosity, resin flow, consolidation, gel time test, shrinkage and voids. We will also look at the basic manufacturing steps which are common to various manufacturing processes used for fiber reinforced composites used in wind turbine blades. And then we will look specifically at the hand layup and spray layup technique. So, if you look at the introduction to the various manufacturing processes of the composites, these are specifically speaking on the polymer matrix composites.

So, these processes essentially get classified based on the type of matrix which is used in the polymer matrix composite. So, as we have seen in the previous lectures, the primary classification of the polymer matrix is based on its behavior towards heat. So, in this regard, we have seen there are primarily two groups of polymer composites which utilize composites either in form of the thermosets or thermoplastics. So, based on this the thermosets as we know are basically polymers which get cross linked and therefore, they cannot be remolded by applying heat. On the other hand the thermoplastics are those polymers which can be remolded upon applying heat and can be reshaped multiple times.

So, based on this fundamental classification the various manufacturing techniques are listed here, which are basically depending on say targeting fiber and resin. Under this category, we have filament winding, pultrusion, resin transfer molding abbreviated as RTM. We have hand layups and spray layup techniques. In the prepreg category, we have the filament winding, pultrusion, again we have the resin transfer molding, hand layup

and spray layup. Then we have the sheet molding compound which is abbreviated as SMC or the bulk molding compound which is abbreviated as BMC in which primarily the compression molding technique is more popular.

If you look at the classification in the thermoplastics, so in this regard, the techniques are somewhat similar, say the filament winding, pultrusion, resin transfer molding, spray layup and hand layup. But other than this, the thermoplastics also utilize other techniques such as tape winding, hot press and autoclave. So, as we can see there is a wide variety of manufacturing processes in the polymer matrix composite. Now, not all the processes are suitable for manufacturing the wind turbine blade which is of course the topic of this course here in this module. So, we will only study the specific processes which target the wind turbine blade, the other processes are not going to get covered in this course.

So, moving ahead we will see what are the fundamentals of manufacturing any polymer matrix composite or polymer matrix composite when utilized for different engineering components. So, in this regard the transformation of the uncured or partially cured fiber reinforced thermoset polymers are more popular. Because as we have seen in selection of the material for the wind turbine blade it is the thermoset in that thermoset also we have seen that in particular to that the thermosets are more popular because, they can be having permanent crosslinks and in thermosets also we have seen specific thermoset that is epoxy based thermosets are more popular because they do not generate any byproducts and they have good fiber wettability and their handling is also much better. And in case of reinforcement we have seen categorically the use of glass fibers and carbon fibers is very popular in wind turbine blades. So, the manufacturing discussion of the manufacturing processes will revolve around the curing of the thermoset which is specifically the grade of epoxy here.

And of course the fibers which are used are basically glass and carbon fibers. So, in this regard the manufacturing of any such composite depends on complete curing of the thermoset into the composite part or structure. So, this curing is basically a chemical reaction in which the cross links are developed. So, curing of the material at elevated temperature and pressure is required for predetermined length of time. So, we need to have appropriate temperature and pressure so that consolidation between various layers of the composite can take place, and this heat and pressure has to be applied for a sufficient amount of time, so that the complete transformation of the liquid resin into a solidified thermoset takes place.

So, higher cure temperature are required to initiate and sustain chemical reaction, that transformed uncured or partially cured material into fully cured solid. So, high pressures are utilized which provide the required force needed to flow the highly viscous resin or the fiber resin mixture in the mold. Because the resin is basically mixed with a hardener to initiate the crosslinking before it is being pumped into the mold and for this proper

flow of the resin high pressure may be needed, and this high pressure may also be needed for consolidation of the various individual unbonded plies into bonded laminate. The length of time required for properly curing the part is called as cure cycle. So, this is very important from the manufacturing standpoint because cure cycle, the length of the cure cycle it determines the productivity of any manufacturing process.

Since, cure cycle it also determines the production rate of the part, it is desired to have the proper cure in the shortest amount of time or the shortest duration of time we should have the proper curing. The cycle of cure or the cure cycle it also depends on other factors such as resin, chemistry, catalyst reactivity, cure temperature and presence of inhibitors or accelerators. So, we will see in little details about these things in a moment now. So, the various factors which are considered while we make selection of the appropriate manufacturing process, not only for wind turbine blades, but for any polymer composite part, they involve these important factors which is degree of cure, viscosity, resin flow, consolidation, gel time test, shrinkage and voids. So, we will see in little detail each of these factors.

So, we start with the degree of cure. So, as we are dealing with the thermosets, so it is very important to estimate that how much thermoset has crosslinked into the complete part. So, this is estimated by this factor known as or the parameter known as the degree of cure. So, degree of cure is basically the ratio of amount of heat released in time  $t$ , and is the rate of heat generation of the isothermal experiment conducted at constant temperature  $T$ . So, here  $H$  is basically the amount of heat released in time  $T$  and  $HR$  is the dynamic heat of reaction in dynamic heating.

So, this is basically estimated using differential scanning calorimetry test. Where, we calculate this ratio that how much heat is getting released once the part is curing and what is the total amount of heat which should be released, if the degree of cure is 100 percent and by taking the ratio of both, the heat released we can estimate the degree of cure experimentally this type of value comes in the range of 0.9 to say 0.99 And ideally the degree of cure should be near 1, but in practical cases it is never equal to 1, but it is always near 1. So, ideally it is desired the degree of cure should be more than 90 percent or more than 95 percent in these cases where we are dealing with components made of polymer composites.

Example in wind turbine blade which are having large size and they are subjected to various types of dynamic loads. So, here we can see the higher cure temperature increases the rate of cure and it produces the maximum degree of cure in shorter periods of time. So, this means that if we elevate the temperature, so the degree of cure can be achieved much faster. And all the manufacturing process they basically utilize heat in some form to provide this heat and thereby we can say that by increasing the temperature we can also

improve the degree of cure, as increased temperature will reduce the cure cycle in the composite manufacturing process. Next is the viscosity.

Viscosity is another important parameter to look at in selection of the appropriate manufacturing process. This viscosity here we are talking about viscosity of the resin or the matrix or it is the epoxy of whom we are talking. The epoxy is basically the material under consideration whose viscosity is being discussed. So, what is viscosity? So, viscosity is basically the of fluid is basically the resistance of which the fluid offers under resistance to the flow under the shear stresses. So, lower molecular weight fluids, for example water or motor oil, they have low viscosity and they readily flow under the influence of shear stresses.

Epoxy especially when mixed with hardener so it has high molecular weight and such polymer they melt at high viscosities and they flow only under high stresses. So, because of this high viscosity appropriate pressure needs to be applied so that the viscous epoxy can flow in the complete mold and thereby completely wet out the fiber which is pre-placed. The important factors that determine the viscosity of the fluid are temperature and shear rate. For all fluids, the viscosity decreases with increasing temperature. Shear rate does not have any influence on the viscosity of low molecular weight fluids whereas, it tends to increase because of the shear thickening or it may decrease because of shear thinning in viscosity of high molecular weight fluids.

Polymer melts especially in general are shear thinning because their viscosity decreases with the increased intensity of shearing. And as we have discussed previously, For the thermosets the viscosity basically first it basically decreases it shows a decreasing trend where the increased energy or heat energy increase the mobility of the molecules. And once the gelation it starts into the thermoset because of the cross linking reaction the viscosity it goes on increasing as we saw in the previous discussion on the behavior of epoxy to heat in the curing. So, this increased viscosity as the curing proceeds needs more high pressure of consolidation so that appropriate wetting takes place and the degree of cure also needs to be achieved nearly equal to 1.

So next is the resin flow. So, resin flow is another important aspect because proper resin flow is desired through the dry fiber network. This is especially important in case the liquid composite molding techniques are used that we will discuss in this next few lessons or these are also important if prepregs are being utilized in specially vacuum bag molding process, which is critical in to produce void free parts and fiber with good wet out. So, resin flow is also important because the resin as we know is much viscous and its flow also needs to be proper into the mold so it is appropriately wetting out the fiber. In thermoset resins, curing might take place simultaneously with resin flow and if resin viscosity rises rapidly during the curing, So then the flow may be inhibited and there may be regions in the composite part where, the flow of the resin has not taken place

completely and because of which voids may be developed and this may lead to poor inter laminar adhesion. So, resin flow through the fiber network is often modeled using Darcy's equation which is derived from the flow of Newtonian fluids through a porous medium.

So, Darcy's equation is shown here on the right hand side which says  $Q$  is equal to negative  $P$  naught by this  $\eta$  and then we have the pressure gradient term here. So, this basically  $P$  naught here is the permeability of the media and we have seen that fibers as they can be woven fibers, they are often porous. So, permeability of those porous fabrics has to be modeled here into in and viscosity here  $\eta$  is basically the viscosity of the epoxy and pressure gradient is basically the pressure which is applied to pump or push the epoxy from the resin tank into the mold. And this is basically having a negative signature, which is basically the direction of flow is positive. So, this equation relates the volumetric resin flow rate that is,  $q$  per unit area to the pressure gradient that causes the flow to occur for one-dimensional flow in the  $x$  direction.

So, this is basically for a simplified Darcy's equation for one-dimensional flow and this equation can also be expanded for three-dimensional flows to look at how the resin flows in the three dimensions if modeling of the resin flow is to be done. Next is the consolidation. Consolidation of the various unbonded plies or laminates is very important in case of composite parts. So, consolidation layers of the fiber network or the prepreg layer, it requires good resin flow and compaction. If the consolidation is not done properly, the resulting composite laminate may contain a variety of defects, which include voids, interply cracks, resin rich areas or resin poor areas.

So, good resin flow by itself is not sufficient to produce good consolidation. Both resin flow and compaction require the application of pressure during processing in direction normal to the dry fiber network or prepreg layer. The pressure which is applied is also useful to squeeze out any trapped air or volatiles as resin flows through the fiber network or prepreg layer which suppresses voids and attains uniform fiber volume fraction. Next factor is the gel time test. So, gel time test is basically the curing characteristic of resin and catalyst.

This catalyst is often referred to as a hardener in scientific literature and this hardener is basically combined with the resin in a specific ratio and this is frequently determined by the gel time test. So, gel time test is a test where a measured amount say 10 gram of thoroughly mixed resin and catalyst is combined and poured into a standard test tube. The temperature rise in the material is monitored as a function of time by means of a thermocouple while the test tube is suspended in 82 degree Celsius water bath. So, then it is estimated at what time and of course at this temperature, how long the mixture takes place to convert into a gel or how fast it reaches the gelation point that is once the crosslinking starts into this resin.

Next is the shrinkage. So, shrinkage is basically the reduction in the volume or linear dimensions caused by curing as well as thermal contraction. So, curing shrinkage occurs because of rearrangement of polymer molecules into more compact mass during curing as the curing reaction proceeds. The thermal shrinkage occurs during the cooling period that follows the curing reaction and may take place both inside or outside the mold. Next are the estimation of voids. So, voids are fundamentally very difficult to completely eliminate in any manufactured composite part.

But it is always desired and always the efforts are put in to minimize the void volume fraction to as low as possible. The presence of voids are often considered as the most critical defect influencing the mechanical properties of the composite part. Because, it is the presence of voids that makes the discontinuous interface between the fiber and the matrix. The most common cause of void formation is the inability of the resin to displace air from the fiber surface during the time fibers are coated with the liquid resin. The rate at which the fibers are pulled through the liquid resin, the resin viscosity, relative values of fiber and resin surface energies, and the mechanical manipulation of fibers in the liquid resin affect the air entrapment at the fiber-resin interface.

Voids may also be caused by air bubbles and volatiles entrapped in the liquid resin. Solvents used for resin viscosity control, moisture and chemical contaminants in the resin as well as styrene monomer may remain dissolved in the resin mix and volatiles during the elevated temperature experienced during curing. In addition to that, air may also get entrapped between various layers of the laminates during the lamination process. So, all efforts are basically done to remove this entrapped air as well as the volatiles that may be produced during the manufacturing of such laminated composite parts and such laminated composite parts are also used in wind turbine blades. Now, if we look at the basic philosophy of manufacturing processes for polymer matrix composite.

So, they utilize these four steps which include the impregnation, layup, consolidation and solidification. So, we will see in detail what each step means. So, impregnation is basically the step in which the fiber and resin is mixed together to form a lamina. So, the purpose of impregnation is to make sure the resin flows completely around all the fibers. Viscosity, surface tension and capillary action are the main parameters that affect the impregnation process.

Second step is the layup step. So, in this step, composite laminates are formed by placing fiber resin mixtures or prepregs at desired angles and at places where they are needed. The purpose of this step is to achieve the desired fiber architecture as dictated by design. Performance of composite structure relies heavily on fiber orientation and layup sequence. So, next step is the consolidation step. So, consolidation step involves creating intimate contact between each layer of prepreg or lamina.

The step of consolidation ensures that all entrapped air is removed between the layers during processing. Fibers undergo elastic deformation while compressive pressure increases the resin flow out towards the boundary. Solidification is the last step in the general outlay of the manufacturing process. In the solidification step, use of vacuum or positive pressure is maintained. Lower the solidification time, higher is the production rate achieved by the respective manufacturing process.

This step ensures that all entrapped air is removed between the layer during processing. In thermoplastics, as we know, there is no chemical change during solidification, so their solidification requires least amount of time. In thermoplastic processing, the rate of solidification is also dependent on the cooling rate of the process. Now, we come to discussion on the manufacturing process which are used in manufacturing of the wind turbine blade. So, these manufacturing process are basically categorized in two types based on the type of mold which are used to make the wind turbine blade.

So, these are open molding mold manufacturing process and closed mold manufacturing process. So, now we will see the open mold manufacturing process. So, in the open mold manufacturing process, these are perhaps the simplest technique to mold composite part. The mold is a single mold which is open from one side.

This is popular for several engineering composites. And processes of hand layup and spray layup, they utilize the open mold to make the composite parts. So, in this regard, there is a concept of utilizing a gel coat. So, a gel coat is basically applied on the outer surface of the part. So, gel coat is applied on the mold, but it ends by being on the part in the complete cured part. So, gel coat is a thermoset resin and is generally sprayed on the mold.

So, mainly intended for protective or decorative surface. So, material of the gel coat is based on polyester or vinyl ester. Sometimes some pigments may also be added for faster curing. So, these are shipped in drum and need to be stored at a temperature between 22 to 25 degree Celsius. Equipment of gel coat needs spraying on the mold and this thickness of the gel coat is between 0.

4 to 0.5 millimeters. So, if we see the hand layup and spray layup technique, so they are perhaps the simplest of the polymer processing technique. Fiber can be laid onto the mold by hand and then resin which can be say unsaturated polyester or other type of resins like epoxy can be sprayed or brushed onto it. Frequently the resin and fibers may be sprayed together onto the mold surface and in both cases the deposited layers can be densified using rollers. So, the consolidation pressure here is applied by rollers and use of accelerators or catalyst can be done and curing can be done at room temperature or moderately high temperature in an oven. So, here we can see the schematic of hand layup technique where we have this open mold as shown here.

Then we have a release film which is basically a plastic film which enables to quickly release the cured part. Then we have the application of gel coat as we have discussed this is for protective and decorative purpose. So, then reinforcements may be placed by hands as shown here the fiberglass reinforcement and a resin may be initiated resin means it is mixed with the hardener is then poured and consolidated using a hand roller. So, here the technique is quite simple, but there may be a lot of variation in the part quality as manual effort is needed here. So, if we look at the other details, so popularly thermoset are used as matrix such as polyester or vinyl esters.

Filler and additives may be added by the molder into the resin manufacturer and they are mostly shipped as need without fillers or reinforcement. Reinforcement of various forms like mats or woven fabrics or knits can be used. Reinforcements are simply laid onto the mold. During wet-out, the fiberglass changes its color aiding the monitoring of the wet-out process. Due to exotherm consideration, the part cannot be too thick as sometimes heat may be released during curing.

After curing, the part is removed from the mold, trimmed and finished. The other technique is the spray layup technique. So, it is used when part of sufficient size that is sufficiently large parts are made and spray can lead to uniformly spreading of the resin and on the reinforcement. So, the advantage of spray up over hand layup is the speed at which the resin fiber can be applied on the mold. Disadvantages of this technique include use of special equipment and use of limited choice of resin and highly skilled labor.

Spraying equipment consists of a chopping mechanism with a spray gun. Fibers are brought into the gun as a roving and are then chopped before they fall into the stream of a resin after the nozzle. Fiber are entrained with the resin and are sprayed together onto the mold and length of the chopped fiber should be short for easily spraying.

Fibre of length 2.5 cm to 7.6 cm is most suitable for spraying and sometimes the fibres may not be used, only the resin may be sprayed, fibres may be pre-placed into the open mould. To ensure the complete wet out of the sprayed fibre, a roller is used to ensure the resin fully wets the fibre bundles. So, here we can see the schematic of the spray up technique. So, here we can see the initiator or the hardener and the resin are being pumped into the spray gun.

And fiber spool is providing the chopped fiber. In several cases, chopped fiber may not be used. The initiated resin may be directly sprayed onto the mold and the fiber may already be preplaced, which is the case with the wind turbine blades. In summary of today's lesson, what we have seen is we have seen the classification of the manufacturing process of the polymer matrix composites manufacturing processes. We have understood various factors which influence the choice of manufacturing process selection. So, selection of the manufacturing process are dependent on these vectors and then we have

seen in detail the hand layup process and the spray layup process, which are basically the process in open mold manufacturing processes.

So, in the next lesson we will see the details on the vacuum bag molding process which is also used to manufacture the wind turbine blade. Thank you.