

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

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**Lecture 29**

Welcome to this course on manufacturing of turbines. So, in this lesson 29 of the course, we will see the manufacturing of the wind turbine. We are continuing our discussion on the material selection of the wind turbine. So, up to now we have seen the classification of the polymer composites which are used in the wind turbine. Because, we know the wind turbine is interacting with the flowing wind and to extract energy from the flowing wind we need lightweight high strength material and such properties are offered by polymer matrix composites. So, in the previous lecture we have seen the details about the polymer matrix, the various additives which are added in the polymer matrix to impart various properties.

So, although we have seen there are several matrices available and the choice even gets larger as new and new matrices are getting developed. So, we have also seen the classification of the matrices based on the behavior to the heat which primarily classifies the matrices as thermoplastics or thermosets. But, to make the wind turbine it is a specific type of matrix which is used as the matrix material. So, in this lecture we will see the details about the specific matrix that is the epoxy.

So, epoxy as we have now understood is basically a thermoset, which is used to make the wind turbine blade. And in today's lesson, we will see detailed discussion on the various aspects of epoxy which will include introduction, chemical structure, classification, synthesis, curing techniques, various properties of epoxy which involve mechanical properties, thermal, electrical and adhesion properties. We will also compare the epoxy with other thermosets such as unsaturated polyester and we will see how these properties they vary between the unsaturated polyester and epoxy. So, epoxy is basically the popular matrix which is a thermoset which is used to make the wind turbine blades. So, this is a class of pre-polymer and polymer which essentially contain an epoxide group.

So, epoxide group is the main group in the epoxy. So, these are the thermosetting resin which cure means upon curing they develop the cross linking. So, when mixed with the curing or hardener, so this cross linking reaction initiates and it is accelerated in presence of heat. So, it was first developed in the year 1930 and from there on it got

commercialized in 1940 for various industrial applications. So, this is second most widely used thermoset after polyester thermoset.

So, it is widely also used not only in composites, but it is also used in several coatings, adhesives, other composites, electronics because of its excellent mechanical properties, chemical resistance and adhesion. So, if we look at the chemical structure of the epoxy resin, so the chemicals in the chemical nature, the epoxy resin has the oxirane ring, which is the reactive site from where the crosslinking occurs. So, it is a process essential to form the final and solid polymer. So, positioning, epoxy group can be attached directly to other organic group denoted by R in chemical representations or to the glycidyl group, epoxy ring is attached to the carbon bridge. So, this epoxy group when attached to the glycidyl group, the structure is composed of the epoxy ring and an additional carbon bridge which is connected to an organic group.

So, importance involves glycidyl group structure affects the resin reactivity and the properties of the cured polymer. So, here we can see the generalized representation of the epoxy group and the glycidyl group. So, in the composition the epoxy ring and the R group, the polymer consists of the epoxy ring and a variable organic group R group, determining the epoxy property. The reactive sites, so epoxy ring act as reactive sites for cross-linking similar to carbon-carbon double bonds in the unsaturated polyester. So, next is the cross-linking density.

So, frequency of the epoxy group like unsaturated polyester where double bond frequently occur in the epoxy resins. The reactive epoxies are mainly located at the ends of the polymer chain or the branch points. So, we can see the generalized representation of the epoxy polymer and this polymer portion is basically having at the end the number of repeating units that is these are the monomers which are combined together in this epoxy chain and, at the end we can see this triangular structure which is the reactive group or the epoxy group which goes on coupling with the next polymer chain and thereby the crosslinking occurs. So, in the industry, there are different types of epoxies which are popularly used. So, different types of epoxies which are available, they involve Bisphenol A grade epoxy, Bisphenol F epoxy, Novolac epoxies.

So, Bisphenol A are basically standard resins with very versatile and balanced properties. Bisphenol F epoxy, they offer lower viscosity and improve the chemical resistance. The Novolac epoxy, they provide enhanced thermal stability and chemical resistance due to the high cross-linking density in these polymers. So, these epoxies based on the application can be selected for the required properties based on certain properties like mechanical strength, chemical resistance or thermal stability. So, here we can see how the chemical structure of the Novolac based epoxy is shown here where we can see the excessive crosslinks they prevent any chemical attacks so thereby providing chemical resistance to this type of epoxy.

Next, is epoxy resin production. So, how the epoxy resin is produced? So, bisphenol A and epichlorohydrin reaction. So, this is the most prevalent method for synthesizing epoxy resin involves reacting bisphenol A with epichlorohydrin. So, this process forms the glycidyl group on both side of the aromatic segment resulting in creation of the epoxy polymer. So, in the reaction process, there are two stages.

So, stage 1 involves formation of the diglycidyl ether or bisphenol A known as the DGEBA. So, in stage 2 to further polymerize to achieve the desired molecular weight and the viscosity, the polymerization is continued. In the final product, the resin can be modified by adding certain additives to tailor the properties such as flexibility, toughness or viscosity. So, we can see here the synthesis of the epoxy by combination of the bisphenol molecule with the epichlorohydrin here. So this is the epichlorodihydrin molecule and this is the bisphenol molecule.

When these are combined, so we can see the presence of the glycidyl group or diglycidyl group at the ends of this polymer chain and the HCl is basically the byproduct in this reaction. So, based on this name that is diglycidyl ether of bisphenol A. So, in scientific literature we will also observe the name of the epoxy as DGEBA that is the abbreviation of this diglycidyl ether of bisphenol A. Next is the curing techniques for epoxy resin. So, curing is basically the main manufacturing step in which we allow the crosslinks to get developed in this type of thermosetting resins.

So, curing of the epoxy is a crucial step in processing the epoxy resin where liquid resin which is of course having high viscosity at room temperature is transformed into a solid material with desired mechanical, thermal and chemical properties. So, this transformation occurs through crosslinking, which is a reaction initiated by a curing agent, which is sometimes also known as hardening agent. Understanding the crosslink and process parameters is essential to optimize the performance of the final product. So, to begin the crosslinking reaction, active sites must be present on the polymer chain. So, in the epoxy group, the active site for the crosslink is the epoxy group, which is typically located at the ends of the polymer chain or the side chain.

So, this differs from unsaturated polyesters where the active site is the carbon-carbon double bond present in each repeating unit along the polymer backbone. So, here we can see that in presence of the hardener, so this is basically the hardener here. So, when this hardener, this combines with the epoxy molecule here, so then this cross-linking occurs and this results in the cured polymer. So, different type of curing crosslinking reaction can occur. So, the first type is the ring opening reaction.

So, in the ring opening reaction, the crosslinking in the epoxy resin is initiated by opening of the epoxy ring by a reactive group from the curing agent. So, the curing agent it provides a reactive group which results in opening of this epoxy molecule. This curing

agent commonly is the amine. An amine group is basically the common hardener which is used to initiate the curing reaction in epoxy. And what is this amine? In the amine we have the nitrogen atom which reacts with the slightly positive carbon atom in the epoxy ring.

So, this presence of this nitrogen atom, it breaks open the closed ring of the epoxy and thereby forming the new bond. So, this ring opening mechanism is in contrast with the free radical addition reaction which is often referred to in the case of unsaturated polyesters. So, in the byproduct discussion of this type of curing reaction, it is very important to note that during curing of the epoxy, no byproducts are produced which greatly simplifies this process. So, this is one of the important points. Another point to note here as no byproducts are produced in curing of the epoxy.

So, therefore it is very popular in structural applications such as high strength, lightweight structures, example the wind turbine blade. This is also in contrast to several other thermoset resins where condensation byproducts or condensates are produced and separately we need to manage these condensates or remove them from the product which increases the overall cost and time in the manufacturing process. But by utilizing epoxy as no byproducts are generated during this process, it greatly simplifies the manufacturing process. So, that is why epoxy is one of the most popular thermoset being used to make wind turbine blades. So, the reactive agent which begins the curing are known as the curing agents or the hardeners.

So, various curing agents can initiate the cross-linking in epoxies. So, this not only includes amines, it also includes amides, acids and phenols, mercaptans and anhydrides. So, these agents, they contain certain reactive groups capable of opening the epoxy ring. So, this choice of curing agent also affects the curing rate, temperature requirement and final property of the epoxy resin. But the main mechanism on which the curing agent they work is by reacting with the slightly positive carbon which is present on the epoxy ring.

So, if we see the different type of hardeners, so we have aliphatic amines which is very convenient and of low cost and at room temperature they may start the curing but they may also cause the skin irritation and they also may need precise mixing ratios. Next are the aromatic amines. So, they offer moderate heat and chemical resistance but this type of hardeners may require long and elevated cure cycles. Third is the polyamide which provide flexibility and toughness but they may also have high cost as well as low heat distortion temperature. Fourth are the anhydrides they are known for heat and chemical resistance but they require long and elevated curing cycles.

Lastly are the catalytic hardeners. So, they have a long pot life with high heat distortion temperature, but they offer poor moisture resistance and also may require elevated temperatures during curing. So, here another term is being introduced that is the pot life.

So, pot life is basically the life or the time which is there after mixing the hardener with the epoxy for how long it can sustain before the crosslink can start, and this may often sometimes become essential as we want to delay the curing so, in this case a longer pot life is desired. Next important criteria or discussion point is the cross linking density and stoichiometry.

So, cross linking density is basically the number of cross links per unit volume and it determines the physical properties of the final product. Higher the number of crosslinks, higher crosslink density, higher is the strength, stiffness and temperature resistance. But, more crosslinks can also result in the brittleness in the final product. Stoichiometric ratio ensures complete reaction at all active sites achieving maximum crosslink and deviations can result in reduced mechanical properties. So, it is very much desired that mixing of the epoxy and hardener should be in the proper ratio as specified by the manufacturer of the epoxy and hardener.

So, here we can see schematic representation of curing various hardener epoxy concentrations and how they can lead to formation of the product. So, here we can see by adding the excess tetra-functional hardener, we have a bi-functional epoxy, so we can have a epoxy hardener product. So, in first case, when the stoichiometric ratio is less, so their thermoset crosslinks may not be proper and if it is in excess amount so then, there may be some transformation in the polymer itself. Here, we can see how the epoxy curing reaction takes place in the presence of amine hardeners which are very popular hardeners with the epoxy. So, as mentioned earlier in the case of amine hardeners the presence of this nitrogen bond is slightly having negative charge and this attacks the slightly positive carbon charge.

Thereby, opening this ring this ring gets opened and then this nitrogen combines with this hydrogen thereby forming this bond which is also known as the cross-linking. So, once the ring of the epoxy is open so formation of this bond results into cross-link and this reaction can keep on sustaining as long as sufficient amount of hardener is present and to accelerate such reaction presence of heat is needed which will be provided by various sources. Next is what is the cure temperature at which the epoxy get cured. So, typically the epoxy are cured at elevated temperature of 121 degree Celsius or 250 degree Fahrenheit. High performance epoxy may need more high temperature up to say 177 degree Celsius or 350 degree Fahrenheit.

Sometimes homo polymerization may also be needed where a reduced amount of hardener is used to allow homo polymerization which requires higher cured temperatures. Next is the cure rate. So, variable cure rates are possible and for epoxy resin it can widely vary from a few minutes to several hours depending on the curing agent and temperature. So, this flexibility it allows several adjustments to meet the specific application requirements.

Next is the pot life. So, adjustable pot life is also needed. So, pot life of the epoxy can be tailored by selecting appropriate curing agent and conditions. So, this allows more control over the working time before the resin starts to set or begins to harden. Next, is use of solvents and diluents. So, less frequent use is noted for the solvents.

So, epoxy resins typically they have higher viscosities and they often do not require any solvents or diluents for processing unlike unsaturated polyesters which frequently use styrene as the reactive diluent. Volatiles from the systems, so in curing of epoxy, very low quantity of volatile compounds are generated which make it preferable in environments where emissions need to be minimized. Especially this becomes important once epoxies are used to manufacture large size components such as wind turbine blades. Next aspect on epoxy is the fiber wet out and viscosity. So, high viscosity and wet out are desirable for the effective wetting between the fiber and the matrix.

So, due to high viscosity of the epoxy, there may be some difficulty in wetting out the fibers in composite applications compared to unsaturated polyesters. However, by using proper processing conditions, this effect can be mitigated and controlled properly. Next is the degree of cure. So, post curing to ensure that cross link are fully formed or not, so we need to maximize the degree of cure. So, this is very much essential for all the thermosets and this step is less frequently required for polyesters, but it is essential to understand the degree of cure in case of the epoxy and techniques like differential scanning calorimetry can largely help us to understand the degree of cure.

Next is the shrinkage. So, low shrinkage. So, generally the epoxy resin they exhibit low shrinkage during curing compared to unsaturated polyester. So, this is also important to provide dimensional stability to the final product especially when product of large size like wind turbine blades are being manufactured. So, here we can see a typical curing profile for an epoxy where the curing is being conducted inside an autoclave. So, autoclave is type of a furnace which can simultaneously apply heat or pressure. So, heat is applied by presence of heating elements or coils and pressure may be applied by vacuum or may be positive pressure by some inert gas.

So, here we can see the beginning of the heating takes after full pressurization of an autoclave which, is also a sort of a pressure vessel. And this type of a typical heating profile is there for epoxy and it can vary depending on the size of the product or maybe the hardener or the other considerations like thickness of the product and so on. So, next are the mechanical properties of the epoxy resin. So, tensile strength, it typically ranges from 50 to 100 MPa and it may also further vary depending on the formulation and curing conditions. Modulus of elasticity, in this case the epoxy generally provide modulus of elasticity between 2.

5 to 4 GPa. Impact resistance of the epoxy may be improved by adding some toughening agents such as, rubber or nanoparticles because typically it is a thermoset and it may be rendered brittle in case of impact loads. So, thermal properties of the epoxy include glass transition temperature which ranges between 50 degree Celsius to 250 degree Celsius depending on the formulation and it is a critical factor in defining operational temperature limits. Thermal decomposition, it begins around 300 degree Celsius with char formation contributing to fire resistance. Thermal conductivity, intrinsically the epoxy have lower thermal conductivity but it may be further improved by adding some fillers like aluminium oxide or graphene or graphite. So, electrical properties in this case the dielectric strength of the epoxy is between 18 to 25 kilo volt per millimeter making it ideal for electrical insulation application.

Insulation resistance also is very good as resistivity is often exceeding  $10^{12}$  ohm per centimeter because of which it is widely used in electrical encapsulation printed circuit board etc. Adhesive properties of the epoxy make it good for several joints. Strong adhesion with respect to various substrates due to polar epoxide groups make it very favorable with interacting with substrate surfaces. And excellent adhesion to metal, glass, ceramic and many plastic make it quite versatile. And it is used in several structural bonding, automotive assembly and aerospace application where high strength and durability are required.

So, here we can see comparison of epoxy and unsaturated polyester. Now we will see the active site on the epoxy where in case of the epoxy there is the epoxy ring while in unsaturated polyester we have the carbon-carbon double bond. So, cross-linking in case of epoxy is the ring opening reaction, in case of unsaturated polyester it is addition of free radical. So, no byproducts are produced in both the cases and we need reactive agents such as bifunctional short polymers in case of epoxy but initiators such as peroxides may be needed with polyester. Hardener may be added in the ratio of 1 is to 1 with epoxy while 1 to 2 percent of the polymer may be added as initiator in case of polyester.

Toxicity of uncured reactants may result in skin irritants and sometimes there may be carcinogenic reactants. In case of polyesters, there may be few problems, but styrene emission can result in some gas emission issues. And use of solvents is less frequent in epoxy, but use of styrene is actively done in case of the unsaturated polyester. In case of processing, so volatiles, less number of volatiles or less amount of volatiles are generated in epoxy curing but relatively high amount of volatiles are generated in unsaturated polyester. Fiber wet out is relatively challenging in epoxy because of high viscosity but because of low viscosity it is easy in case of polyester.

Cure temperature some mostly elevated temperature is needed and it might also get cured at room temperature but it will take longer time. Whereas, the polyester it gets easily cured at room temperature. So, accelerators are not added in case of the epoxy and

sometimes accelerator or promoter may be added to accelerate the or accelerate the curing rate in case of polyester. Cure cycle times are longer in case of epoxy and these are short to moderate in case of polyester. Pot life is adjustable by adding the amount of the hardener but in case of polyester it is short.

And rarely we use inhibitors in the case of epoxy but inhibitors may be frequently used in case of polyester so as to enhance the pot life. Inhibitors are basically components added in the thermoset to inhibit the crosslink or slow it down. So, filler may be occasionally added in case of epoxy and these may be sometimes added in high concentration in case of polyester. Degree of cure is done to be estimated post curing and in case of unsaturated polyester rarely it needs any post curing to achieve the required degree of cure. In case of epoxy there is low shrinkage, in case of polyester there is high shrinkage which makes epoxy much desirable for making products with good dimensional stability.

So, these are other properties of the epoxy which can be looked at in terms of adhesion, shear strength, fatigue resistance, stiffness, creep, toughness and so on. And we will observe in all these properties epoxy they have better properties compared to unsaturated polyester. Thereby, making the epoxy very suitable for making the wind turbine plates. So, in summary of today's lesson what we have seen? We have seen detailed discussion on various aspects of epoxy, which is the preferred choice of matrix and it is a thermoset, we have seen this.

We have seen all the details in terms of chemical structure. We have seen various properties of epoxy and how these properties they make epoxy so favorable for it to be used in wind turbine blade. Essentially these properties we have no byproduct being generated in the curing reaction and good dimensional stability. These are some of the important properties which make epoxy much suitable for manufacturing the wind turbine blades. So, in the next lecture, we will see the discussion on various properties of the reinforcements which are used in manufacturing of the wind turbine blade. Thank you.