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

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Lecture 32

Welcome to this course on manufacturing of turbines. In this lesson 32 of this course, we will see manufacturing of carbon fibers. So, the outline of this lesson will be as follows. First, we will discuss the introduction to carbon fibers. We will go through the historical context of carbon fibers. We will also understand different types of carbon fibers which are available to make composites.

We will look at the manufacturing of carbon fibers, surface treatments and properties of carbon fibers. And lastly, we will see how carbon fibers are being utilized in several engineering applications which also of course include the wind turbine blades. So, carbon fibers are one of the most popular reinforcements used in composite material. These are especially popular in applications where high strength lightweight properties are desired.

So, carbon fibers are primarily composed of carbon atoms arranged in long chains. So, the fibers consist of carbon atoms which are bonded together in microscopic crystals that are more or less aligned parallel to the longitudinal axis of the fiber. High strength to weight ratio and rigidity of the carbon fibers are another set of attractive properties. So, tensile strength ranges from 3.5 GPa to 7 GPa with low density between 1.

7 to 2 g per cubic centimeter. Young's modulus of carbon fiber, it can range between 200 GPa to 900 GPa. Carbon fibers are a preferred choice of reinforcement where low weight and high strength are critical. So, these are especially used in aircraft wings, car chassis and sports gears. So, if we see the historical context of carbon fibers.

So, carbon fibers were initially used in the 19th century by Edison as carbon filaments in light bulbs. So, these early carbon fibers were crude and were formed by carbonizing bamboo. In the 1950s, key significant and scientific breakthroughs led to modern carbon fibers. Significant development of carbon fibers from synthetic precursors like PAN that is polyacronitrile and rayon was used. So, PAN and pitch based fibers were commercialized in 1960s.

Where, these fibers they offered much higher performance enabling use in aerospace applications like rocket nozzles and aircraft structures. The PAN based fibers are most widely used carbon fibers that offer a balance between tensile strength which is in the range of 5 to 7 gigapascals and a modulus of 230 to 350 gigapascals. PAN is basically the precursors for more than 90% of the carbon fibers that are used in several engineering applications. There is another precursor which is used to manufacture the carbon fibers which is pitch based. So, pitch based are basically derived from petroleum based pitch which offer higher modulus between 500 to 900 gigapascals.

They are widely used in thermal management that is, where we want to remove heat quickly but they offer lower tensile strength. Pitch based fibers can be categorized into isotropic that is of relatively lower quality and anisotropic which is of high performance. Then we have rayon based fibers. So, early fibers from rayon precursors were developed. Nowadays these are less common due to low mechanical performance and complex production process.

Next we look at the manufacturing process overview of the carbon fiber. So, carbon fibers are one of the expensive reinforcements which are used in manufacturing of several lightweight high strength composites. So, manufacturing of carbon fibers is a complex process which involves several stages of heating. So, in this regard the manufacturing process starts with the stabilization process. The stabilization is basically a heat treatment process which can create thermally stable fibers.

The heating of the precursor that is either pan or pitch is done in the range of 200 to 300 degree Celsius in presence of oxygen to form a thermally stable structure. The next step in the manufacturing of carbon fibers is the carbonization step. So, this step involves high temperature process to remove non-carbon elements. Heating in range of 1000 degree to 1500 degree Celsius is done in an inert environment of nitrogen to remove hydrogen, oxygen and nitrogen atoms resulting in 90 to 95% carbon content. The next step in the manufacturing of carbon fibers is the graphitization step.

So, in this step further heating is carried out to enhance the crystalline structure. Optional step of above heating above 2000 degree Celsius is done to align the carbon fiber into a more graphitic structure thereby increasing the modulus of the carbon fiber. Then, there is the surface treatment step that enhances the bonding between the carbon fiber and the matrix materials. Surface functionalization of carbon fibers is carried out using electrochemical processes that introduces carboxyl or hydroxyl groups to improve adhesion with resins. So, we will see schematically the whole of the manufacturing process of the carbon fiber.

So, as discussed, so carbon fiber can be manufactured using two types of precursors. This involves PAN or it can also involve PITCH that is derived using petrochemical products or byproducts here. So, pan is basically available in form of threads, pan is polyacrylonitrile. So, by using either of this precursor, so this is we can say is the precursor. So, here we can take either of this and then the process is common.

The first stage involves the stabilization as just we have discussed. So, here this is we can say the stabilization step and this takes place in air and this is conducted in the temperature range of 200 to 400 degree Celsius and again a continuous tension is applied on the fibers. So, next is the carbonization stage where, we have again use of tension or tensile forces and this stage is known as the carbonization in nitrogen. So, this carbonization is conducted in temperature range of 482 degree Celsius to around 1482 degree Celsius. Next stage is basically the graphitization stage.

Again, use of tensile forces is there, graphitization in nitrogen and this is even conducted at a much higher temperature range that is 1900 to 3300 degree Celsius. After that the fiber it passes to the electrolyte bath. So, here we can see after that it will come in to the electrolyte path wherein the impurities may be removed. Now the use of tensile process is not there. Electrolytic, this is the electrolytic bath after which it will go to the washing.

So, here this is the washing stage where, excess electrolyte may be removed. Next, it comes to the application of sizing which as we have discussed in the glass fiber also. Sizing is basically a chemical applied, so that there is no abrasion or surface defects being introduced on the surface of the fibers. So, the sizing is that chemical which is applied. And after the sizing is being applied the fiber is dried in a dryer and then what we have is the fiber is wound over a spool and we get this type of a thread of the carbon fiber.

So, we can see this complex set of stages which are involved in manufacturing of the carbon fiber. And because there is a multiple steps being involved and additionally the temperature which is there is keeps on increasing with every passing stage. This makes the overall process of the carbon fiber much complex. So, now we will understand what happens at the molecular level at each stage and how that changes on the molecular level. They ultimately influence the overall properties of the carbon fiber.

So, when we heat the precursor fibers in the air in the temperature range of 200 to 400 degree Celsius, the pan that is there in the precursor, it gets oxidized and cross-linked. So, this transforms the structure of the pan from the open type of a structure into a stable ladder polymer resistant to melting. The oxidation forms a ladder-like polymer structure. The nitrile groups in the pan, so they undergo cyclization and oxidation, thereby converting the linear polymer chains into thermoset structures. So, here we can see this in the full atomic scheme.

So, this is basically the pan, atomic structure of pan, and how this upon heating between 200 to 400 degree Celsius, the cyclization of this triple bonded nitrogen takes place and the open or a linear structure of this polymer, it starts converted into this cyclic structure. So, if we look it in a more simple way, so we can say that this type of an open structure, it converts into this type of a cyclic structure or a structure with some closed rings. So, we also need to ensure the fibers, they do not melt during the carbonization process. So, this process is therefore also known as the stabilization process, which is critical to prevent melting or fusion of the fibers during subsequent high temperature processes. Means we are conditioning the fiber at this stage, so that they do not undergo degradation or melting because as we have seen in the overall schematic where carbon fibers are being manufactured, that subsequent stages they offer more or in the subsequent stages the fiber is exposed to more higher temperatures.

So, it needs to be stabilized before we go to that step and to help that the stabilization process or the oxidation process is of much help. So, what happens in the carbonization step? So, as we have seen carbonization step it is carried out in an inert environment where use of nitrogen is popular because of its inert nature and easy availability. So, in the inert environment heating is done in the temperature range of 1000 to 1500 degree Celsius and in this exclusion of oxygen is vital to avoid combustion typically conducted in hydrogen or argon atmospheres. So, this step of carbonization, it helps to remove hydrogen, nitrogen and other elements. Yields with the fiber or carbon content upwards of 90%.

It removes hetero atoms and volatile compounds. The fiber become 90 to 95% carbon. The process produces a turbo static carbon structures, a disordered arrangement of carbon layers. So, here we can schematically see that in the dehydrogenation or carbonization step, the hydrogen which is present here is systematically removed from the rings. And in this case, the carbonization is complete.

So, next step is the graphitization step as we have seen. So, under the graphitization step more high temperature up to order of 2000 degree Celsius is utilized. So, high modulus fibers may also be subjected to 3000 degree Celsius. So, the objective of conducting graphitization is to enhance the modulus of the fibers by aligning carbon atoms into crystalline graphite structures. So, high temperature treatment which is used in graphitization orders the carbon layers into well-defined graphitic planes, therefore increasing stiffness and modulus which can go to as high as 900 gigapascals.

This is critical to achieve high stiffness in advanced application where minimal deflection is needed in for example space structures and satellite components. So, we can see in the graphitization which is also known as denitrogenation process the use of high temperature removes the nitrogen here. Thereby, removing the nitrogen also from the rings and we can see that the graphitic rings of the carbon are developed in this stage. So, after this we enter the surface treatment step in the manufacturing of carbon fiber. So, in the surface treatment step we have seen the use of electrolytic treatments which are used to introduce functional groups also helps to remove the impurities from the surface.

So, commonly polar groups are being introduced on the fiber which include the carboxyl and hydroxyl groups on the surface via anodic oxidation. So, surface treatments they are also known to improve the interfacial bonding between the fibers and the matrix that is the resin matrix and carbon fibers are chemically inert in general and they may have poor adhesion if chemical treatments are not applied. So, advanced methods like whiskerization and vapor deposition, they may also offer superior interfacial properties. Techniques like vapor growth, carbon fibers or depositing nanoscale whiskers further enhance interlocking between the matrices. So, next we will look at the key properties of carbon fiber.

So, PAN based fibers, they offer a balance between strength and stiffness. So, their properties have tensile strength in the range of 5 to 7 gigapascals and a modulus of 230 to 350 gigapascals. As we have seen the pitch based fibers they are used for high modulus and high thermal conductivity. Their modulus range is between 400 to 900 gigapascal and they can have thermal conductivity of the order of 1000 watt per meter Kelvin which is almost comparable to copper which is one of the best thermal conductor. Comparison of tensile strength and modulus density and resistivity across different type of fibers in this case the pan based fibers they offer versatility.

Pitch based fibers they excel in application that need high modulus and conductivity. So, we can see properties of various carbon fibers which are available based on the type of precursor. So, in case of pan based precursor we have three types of carbon fiber which have the standard modulus carbon fiber, intermediate modulus and ultra high modulus carbon fiber. In pitch based also similar nomenclature is being followed. And rayon-based fiber, as we have seen, these are not much popular these days because of their complex processing conditions.

So, we can see the various values of the tensile strength and tensile modulus. In the brackets, the values are presented in megapascals and gigapascals respectively in tensile strength and tensile modulus. So, we can see they offer very high values of these properties thereby making them very suitable for wind turbine blade like application. Now, next is the discussion on the properties that carbon fibers offer. So, as we have seen carbon fibers they offer high strength, high stiffness, high tensile modulus properties.

Now, the question is why such properties are possible with carbon fibers. So, as we have seen the manufacturing process of the carbon fiber where, we start with an open linear chain like structure in pan and then we end up with a closed ring type of a structure and we also conduct various processing of the pan based fibers to remove other atomic species from the carbon or from the polymer chain, thereby leaving only the carbon-carbon bonds. So, carbon-carbon bonds as we know are one of the strongest bonds in nature. And these carbon-carbon bonds and along with the presence of carbon in form of this graphitic atomic structure as shown here, this type of graphitic rings, they offer very high strength because of the strong covalent bond between the carbon-carbon bonds. So, these carbons are present in the graphite here and this bond between each of this carbon is basically a very strong covalent bond.

This is also coupled with the inter-atomic spacing of these basal planes of the graphitic atomic arrangement and distance between this carbon-carbon along the adjacent carbon that is 1.42 angstroms that is the adjacent carbon atoms, and diagonally opposite carbon atoms are at a distance of 2.46 angstroms. So, this unique structure of the carbon fiber inside the carbon fiber, the carbon atoms are arranged in this unique structure with the strong covalent bonding and many a times this strong covalent bond is of course aligned with the fiber axis. Thereby, we have seen that in several composite application whenever the fiber axis is aligned with the direction of loading the properties are substantially high.

So, this is because of this atomic structure and strong covalent bonding. So, we will summarize here this is because of this unique atomic structure and the strong covalent bonding between the carbon-carbon atoms results in high properties of carbon fiber. So, next are some other properties of carbon fibers. These include high strength, high stiffness, high toughness and less weight. Carbon fibers are also unique in terms of their coefficient of thermal expansion which is negative in this regard.

So, it is a special case where we have a negative coefficient of thermal expansion. Wherein as the temperature goes up the sample or the carbon fiber gets small. The carbon fiber also have one of the highest thermal conductivity even it may surpass most of the metals and carbon fibers because of this may be used in several heat pipes in radiators which transmit heat away from the heat source. Carbon fibers are elastic to failure at normal temperatures. Meaning that they do not deform before failure which renders them creep resistant and not susceptible to fatigue.

They are chemically inert in strong oxidizing environments and they are also inert when in contact with certain molten materials. Carbon fibers are also known to have excellent damping characteristics as well. So, because of this application, not only in wind turbine blades, the carbon fibers also find several applications in aircraft control structures increasingly, especially full fuselage of the aircraft may be made out of carbon fiber, helicopter, rotor blades, wind turbine blades, aircraft structural parts such as door, landing gear assemblies, automotive drive shafts, leaf spring, racing car bodies, frames, space rocket and missiles, and high-precision tooling are some of the other applications of carbon fibers. Based on their thermal properties, they are used as heat shields in several missiles, rockets and brakes. They also may be used as aerospace antennas because of low coefficient of thermal expansion.

Space structures for telescopic mounts, housing for computers, small motor, electrical control panels. Because of their chemical inertness, they have been utilized in storage tanks, rigid structures, uranium enrichment, centrifuge in nuclear industry and because of their fatigue and self-lubrication they are used in textile machine components, air slide valves, blades of compressor, artificial limbs. So, in summary we have seen the various properties of carbon fiber. We have looked at the manufacturing process of carbon fiber.

Manufacturing process of carbon fiber. We have also understood the atomic structure and arrangement of atoms in carbon fiber which offers them unique properties and other than this we have looked at applications of carbon fibers in not only wind turbines but several other engineering products. So, with this we have completed the discussion on the various matrices which are used in wind turbine blades which are popularly epoxies. We have also seen the reinforcement which is used in wind turbine blade which is the combination of glass fiber and carbon fiber. We have seen separately the manufacturing process for both that is glass and carbon fiber. Now, from the next lecture we will see the manufacturing of wind turbine specifically utilizing specialized manufacturing process, wherein the raw material will come in form of some resin that is epoxy and reinforcement will be in the form of carbon or glass fibers.

So, we will see the hand layup and the spray layup process in the next lesson. Thank you.