

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

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Lecture 09

Welcome to this course on manufacturing turbines. In lesson 9 of this course, we will see details about the manufacturing of gas turbine blades. The outline of this lesson is as follows. We will discuss the basics of metal casting, which is the primary process to develop gas turbine blades. We will understand how the solidification of metals and alloys differs from each other. We will look at the effect of cooling rate on the casting.

We will look at the role of inoculants. Subsequently, we will look how investment casting process is done for manufacturing of single crystal casting of gas turbine blades. Metal casting is a well-known manufacturing process. It is perhaps one of the oldest manufacturing processes in which the metal is basically allowed to take the shape of a cavity.

So this cavity is developed inside a mold using a pattern, and the pattern is subsequently removed, leaving the cavity. What is left behind is subsequently filled with molten metal. The molten metal is then allowed to solidify in this cavity and Upon solidification, the molten metal takes the shape of the cavity, and the solidified part is subsequently removed. So these are the main essential steps in any casting process. To do the sand casting, for example, is shown here, where we have two parts of the mold: the upper part is known as the cope, and the lower part is known as the drag.

So here, the mold is made up of sand, specifically speaking of green sand. And then all these, you know, getting design is introduced in the mold where we have the pouring cup and the down sprues. Subsequently, we have a runner, then we have a riser, then from the riser, we have the cavity, and sometimes we may also introduce cores to produce hollow parts in between. So this is the fundamental principle of metal casting. Now we will understand what happens during solidification.

Now casting can be done for pure metals as well as alloys, but pure metals are seldom used in engineering components. Nevertheless, it is important to understand the solidification of pure metals because this makes the solidification of engineering alloys

easy to understand. So pure metals, as we know, have a defined freezing point. So what happens once the liquid pure metal is poured is that immediately the temperature will drop, as shown here, and once the temperature reaches The freezing point is so, from there on, the temperature will remain constant. During this phase, the latent heat of fusion is lost, and in this middle phase, both the liquid and solid phases coexist.

Once the freezing ends, there is a further drop in temperature, and the complete solidification of the part takes place. If we plot the density versus time for the same solidification route, then in this case, as the solidification progresses, there is a gradual rise in the density of the product. During the loss of latent heat of fusion, there is a sudden increase in density as more and more liquid converts into solid. And upon entering the end of the freezing stage again, there is a gradual rise in density. So, now everything here is taking place at a fixed temperature because in pure metals all these freezing points and melting points are defined at a single value of temperature.

So here we can see how the gray cast iron, for example, is solidifying. Now, it is important to note that the solidification commences from the edges of the mold. So edges of the mold what I mean by edges so the ends of the mold are basically at ambient temperature. The edges of the mould play an important role in starting the solidification, and then grain growth takes place from the edges. As more and more heat is lost, as shown here, over a span of, say, 11 minutes, 40 minutes, and so on.

So you can observe that more and more grains get solidified. But everything is connected to the edges of the mold as heat loss or heat transfer takes place in the direction opposite to the direction of grain growth in the casting of metals. So now we will understand the solidification of alloys. So most of our engineering products are made up of alloys rather than pure metals because we have improved properties when we mix certain elements together to form alloys. So in alloys, the difference between the alloy and the solidification of the alloy and metal is that in case. The clear defined freezing point or melting point of the alloy is not available; rather, we have a liquidus temperature and a solidus temperature.

So, what happens once we pour any alloy for solidification? So, once the temperature hits the liquidus temperature level, so after that the solidification progresses and in between the solid and liquid phase, so there is a mushy zone. So, what we mean by the mushy zone is the coexistence of the solid and liquid in between, and upon further drop in temperature, of course, the solid alloy is generated. Now the controlling of this solidification rate can largely control what happens in the mushy zone, which is characterized by the presence of these dendrites. So these dendrites are nothing but these are like you know arms, which are spaced out in three dimensional space, and these presence of dendrites can have certain important aspects on compositional variation, micro segregation and micro porosity which needs to be taken care of.

So in the solidification of alloys, the rate at which the alloy is cooling largely decides the size and orientation of these dendrites. So here we can see the solidification of carbon steels, which are alloys. So here we can see that as the percentage of carbon is increasing as from 0.05 to 0.1. So in the second case it is the carbon percentage is 0.25 to 0.3. In the third case it is 0.55 to 0.6.

Now based on the carbon percentage there is a drastic change in the solidification pattern of this alloy because presence of carbon in the alloy it largely changes the liquidus and solidus temperature. and accordingly the dendritic structure gets changed. So, that is why it is very important to understand how various alloys they solidify and what is the role of solidification rate on the end microstructure So I can say that with increased cooling rate. we move from the columnar dendritic structure to equiaxed dendritic structure and further increase in the cooling rate can result in equiaxed dendritic structure. So why this happens? So this happens because when we increase the cooling rate so the tendency to form grains or the opportunity to form grains increases because there is sudden loss in heat so therefore many localized regions in the metal liquid metal they start solidifying because of which instead of having long dendritic structure we have short grains which are termed as equiaxed non-dendritic grains So here also we can see how the different types of the structure can be generated and here there is an important role of inoculant.

So what is an inoculant? So inoculant is a seed on which the liquid metal or alloy can start solidifying. So what I mean by this is that once we introduce these seeds, now seeds means these are solidified metals or solidified regions which are introduced in the melt and on these regions as the temperature drops the surrounding metal. For example here suppose the inoculants are added. Now all the surrounding liquid metal will start solidifying because now it has got a surface on which the grains can start to develop. So, by providing inoculants we provide an opportunity for the liquid metal to come into equiaxed structure.

So, now the question arises why the equiaxed structure is favored so much. So, for applications generally at which are functioning at room temperature and so on, the presence of grain boundaries is very useful because these grain boundaries they inhibit the dislocation movement. because once we have the long grains as shown in say columnar dendritic structure so these long grains are not very favorable for enhanced mechanical properties because there the presence of lesser number of grain boundaries and larger grains so larger grains are generally characterized by more defects, porosities and impurities So we want to have finer grains with more grain boundaries. So finer grains means the grain size will be small, the number of grain boundaries per unit volume will be high. because of which the dislocation moment will be impeded.

Now, this is favorable at room temperature. So, many a times the inoculants are deliberately added and they provide these seeding locations on which the surrounding liquid metal solidifies and we develop the equiaxed structure. So, equiaxed is basically a fine-grained structure and sometimes the inoculants are also known as nucleating agents. Nucleating means they nucleate the sides of solidification for the liquid metal. So, we can summarize here that at room temperature, presence of grain boundaries is helpful to impede dislocation movement.

But as you know we are dealing with manufacturing of gas turbines, specifically speaking of gas turbine blades. So, these are not operating at room temperature rather these are operating at high temperature. So, high temperature means temperature of the order of say 1300 degree centigrade. So, now what happens at this high temperature? Now at if we have this value of high temperature and we have presence of dynamic loads and on top of it if we have the gas turbine blade which is having several grain boundaries. So, what this will result? This combination will result in creep failure.

So creep failure is a form of failure of components under constant load and elevated temperature. So constant load and elevated temperature it results in creep failure. So how this creep failure takes place? because now we are dealing with a structure which is having several grain boundaries. So, say under influence of the external load P and of course, there is temperature T . So, this grain boundaries what happens? This grain boundaries they under influence of increased load and temperature there is sliding of the grain boundaries.

So, sliding of the grain boundaries takes place and because of this sliding the failure of the material or the component can take place. So it is highly desirable that the gas turbine blades they should have no grain boundaries present in them in order to avoid the chance of creep failure. So to do that we have specialized casting processes that we will now see. so primary shaping of the gas turbine blades, it is done utilizing the investment casting process. As we have seen in some of the previous lessons, casting is a very wide topic; there are many processes.

But specifically with gas turbine blades, it is only the investment casting process that is utilized because the investment casting process can manage complexity. Shapes can manage near-net shapes. Complex shapes we have understood that gas turbine blades have an aerofoil structure, which is quite complex, and near net shape is indicating that. Whatever the shape of the product, it is almost near the final shape, so very little subsequent processing may be needed to change the shape; that is what is meant by near net shape in the investment casting process. Produces the complex and near-net shape with excellent surface finish and tighter tolerances.

So because of these attributes, the investment casting process is very favorable for manufacturing the gas turbine blades. The investment casting process starts with the development of a wax pattern. The investment casting process is also known as the lost wax process. So in this regard, the pattern is developed by injecting liquid wax into a metallic mold. So the metallic mold has a cavity that is a replica of the object that will be cast using that wax pattern.

So once the molten wax is injected into the mold, the wax pattern is allowed to develop by solidifying the wax. Upon solidification, the wax pattern is ejected from the mold. So we may have several wax patterns together that are attached to a wax sprue, and then they are invested in a ceramic slurry. So this means they are dipped in the ceramic slurry to develop a layer of specific thickness around it. So then what happened? So then this invested wax pattern in the ceramic slurry is taken to a furnace where it is baked to dry.

Baked and dried out, during this process the wax is melted out. and we are left with a hollow cavity with surrounding solidified ceramic slurry in this hollow cavity. Subsequently, the metal is poured, and then the metal is allowed to solidify in the cavity generated around the solidified ceramic slurry. Upon completion of solidification, the invested material is broken away, and then we are left with the cast product. So all these things that we have just discussed are again mentioned here in the sequence that states that a wax pattern is used. A refractory material is basically zircon, which is a ceramic material used in the ceramic slurry with a binder to coat it around the pattern.

Wax is subsequently melted out. The mold is then destroyed to remove the wax. It is also known as lost wax due to this process. And it can manage all the metals, especially the precious metals, refractory metals, and reactive alloys. And the process may have several variations because of blends of resin, fillers, and wax. It may also use thermoplastic resins instead of wax.

Ceramic and water-soluble cores may also be used. So, in terms of design aspects with respect to investment casting, all the investment casting processes can manage very complex castings with unusual internal configurations. Because in the case of a gas turbine blade, it also has an aerofoil shape and is a hollow blade, this type of complex shape is managed by an investment casting wax pattern, which must be easily removable from the mold. Complex shapes may be assembled into several similar shapes, and there is a practical way of producing, say, threads on hard machine materials.

A uniform section may be preferred. So, it can manage section, maximum section thickness of 75 millimeters with maximum dimension up to 1 meter. So, this is well within the size or the size range of one gas turbine blade, and the weight that the investment casting can manage is 0.5 to 100 kg. So here, the one gas turbine blade is well

within this range, so we can see the tolerance that the process can produce. The tolerance is essentially the acceptable deviation in the dimension.

So here we can see that very tight tolerances of the order of 0.05 to 0.07, maybe plus or minus millimeters, are produced. These are very tight tolerances produced by investment casting. Not only the gas turbine blades, but investment casting is also utilized to manufacture certain other parts like machine tool parts, aerospace components, and valves.

And pump casings, pipe fittings, automotive engine components, decorative work, optical instruments, small arms, and gear blanks. Now, coming back to the topic of the single crystal casting process, we have seen that in the case of the presence of grain boundaries at elevated temperatures. Because of the grain boundary sliding, the creep failure may take place. So, it is highly desired that the gas turbine blades either should have no grain boundaries or if there are grain boundaries so they should be aligned in a specific direction so they provide a strengthening to the microstructure rather than providing opportunity to undergo creep failure so in this regard the nickel based super alloy blades as shown here with a different type of microstructure like equiaxed grains or columnar grains and single crystal are shown placed in the order of increased creep resistance. Means the creep resistance will keep on increasing from left hand side to right hand side as a function of reduced number of grain boundaries per unit volume in that material.

So now to achieve the single crystal casting in the gas turbine blades, of course, we start with the investment casting process to develop the mold cavity by utilizing the wax pattern. Now pouring of the molten metal and then allowing it to solidify is done using specialized furnaces which allows single crystal of the material to develop. So, one of that furnace which we are now discussing is known as the bridgman furnace. So, bridgman furnace is a very popular furnace which is utilized to develop single crystal cast gas turbine blades. So, the bridgman furnace the overall schematic as shown here is basically discussed as follows.

So, the bridgman furnace is surrounded by a heating zone on top. So the upper part is basically the heating zone and the lower part of this furnace is the cooling zone. So whatever shell mould is created using the investment casting process is placed in the hot zone of this furnace. which is connected to a crucible from a crucible we pour the molten material so molten material in this case will be nickel based super alloys, as we are manufacturing gas turbine blades so upon pouring the molten super alloy so it enters the shell mold and then what happens is basically it is allowed to go into the shell mould and the solidification process will start. Now the difference between this furnace and any other generic furnace is that such furnaces they have presence of a grain selector.

Now presence of the grain selector is very important because grain selector is a small opening in the overall furnace cooling zone which only allows a single grain size to pass through it so as that single grain is only developed. Sometimes there may be some seeding materials placed on this cooling plate in the cooling zone. So they may also help in seeding the single grain and as the solidification progresses the chill plate or in the withdrawal unit is brought down at a very gradual rate so that the overall grain growth takes place in a specific direction and at a slower rate this means only one grain will grow because of the grain selector. Subsequently, this results in a single crystal or a single grain type of a microstructure in the gas turbine blade. So, the chambers in the bridge band furnace, they are separated by a radiation baffle because we have two distinct zones that is the hot zone and the cold zone.

So, using a radiation baffle, both of them are separated. suitable vacuum is also achieved before the mold is raised so as to avoid any chances of oxidation the upper chamber that is the hot chamber of the Bridgman furnace is maintained above the liquidus temperature so as to constantly have the liquid solid liquid nickel based super alloy using graphite heaters so these heaters are present here surrounding the hot zone from all the sides And alloy is contained in the shell mold and mold withdrawal rate as I just mentioned is programmed such that from the heating to cooling zone it is done at a few millimeters per minute allowing it to a gradual solid liquid interface which will result in a single crystal grain via the grain selector. So directional solidification is possible to develop columnar grains with elongated in the direction of withdrawal. So absence of transverse grain is there in case of we have directionally solidified grains. So grain selector is added at the blade bottom and the starter top.

So this is typically a pigtail shaped spiral opening. which ensures that every time a single grain enters the casting cavity resulting in a monocrystalline form. Sometimes as discussed earlier alternative seeding may also be introduced at the base of the casting and processing conditions may need to ensure that seed is not entirely remelted. So, grain growth orientation with seed result in single crystal structure from bottom to top. So with this we come to the end of this lesson and now we will summarize what content is covered in this lesson.

We have understood the basics of casting. We have also understood solidification of pure metals and alloys. We have looked at the investment casting process. We have also looked at how investment casting process is then coupled to Bridgman furnace which is important to develop single crystal cast structure. And we are interested in this as we have understood that single crystal cast structure they have no grain boundaries.

So, the tendency of creep failure is minimum. So, in the next lecture of this course we will look at other specialized furnaces or equipment which are used to develop single

crystal cast gas turbine blades which are liquid metal cooling process, gas cooling process and dipping and heaving process in the next lecture.

Thank you.