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

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Week -02

Lecture 08

Welcome to this course on manufacturing for turbines. So, in this lesson 8 of this course, we will start with the manufacturing of gas turbine. So, we will start this topic of gas turbine manufacturing by introducing the gas turbine and its functioning. So this lesson 8 will cover the introduction to gas turbines with the following subtopics which include Brayton cycle which is the thermodynamic cycle on which the gas turbines operate, materials and design of turbine blades. We will look into superalloys, their composition and structure, properties and application of superalloys which are used to make the gas turbine blades. We will also understand the mechanisms behind the performance of superalloys.

Then we will look at the process requirements and outline of the manufacturing processes starting with the primary process to tertiary process to manufacture the gas turbine blades. So gas turbines, they operate on this thermodynamic cycle known as Brayton cycle. So Brayton cycle is used where we have a compressor as shown here, we have a combustion chamber, then we have a turbine. So generally the compressor and turbine are connected and the work output from the turbine, it may be connected to a generator here.

And this generator will subsequently use to produce electrical power. So, in the Brayton cycle, so this is basically consists of four steps. So, step number one - in the P-V diagram we can see it goes from point 1 to point 2 which is the isentropic compression. Then at point 2 to 3, there is heat addition at constant pressure which is denoted by qin. So, this 2 to 3 takes place in the combustion chamber where combustion of natural gas or maybe other fuel like kerosene etcetera can take place.

So here all the hot gases which are produced are brought on the turbine and the hot gases they expand. So from 3 to 4 there is isentropic expansion and then 4 to 1 is basically the heat release to the environment through qout shown by qout. So, similar processes are shown on the T-S diagram just to have the idea of the functioning of the gas turbine in totality. So, we can understand various stages in Brayton cycle using this diagram where in step number 1, there is the intake step where air is drawn into the compressor. In step 2 the compression of the incoming air is done and compression of this air what it does is it increases the air pressure and since the pressure is increased work is done on the air the temperature of the air also increases.

So, then this compressed air is brought into the combustion chamber. where fuel is injected and ignited so that hot gases are released upon combustion of the fuel. So, then hot gases are then brought on to the turbine where the expansion of the hot gases takes place. and while the hot gases they expand over the turbine. So, these hot gases they cause the rotation on the turbine blades and then this rotational mechanical energy is converted into generating power as I discussed by connecting a turbo generator and subsequently the used exhaust gases are released into the atmosphere.

Now, functioning of the Brayton cycle is essentially dependent on the how high is the temperature of the hot gases and what is the lower extent of the temperature of the exhaust gases. So, to increase the efficiency of Brayton cycle, it is desired that the temperature of the hot gases should be as high as possible. So, to do that, we have to also look at the materials that will be interacting with the hot gases in the turbines. So here we can see how a typical natural gas turbine power plant operates. So here the natural gas turbine power plant it operates in tandem with the steam turbine.

So here what happens that we have the compressor and the turbine gas turbine attached. So air intake takes place. And then after the air is compressed natural gas is also introduced. Combustion takes place. Exhaust gases are then used in the heat recovery boiler to generate steam which separately run a steam turbine here.

And whatever is the waste gas after heat recovery from the boiler is sent to the atmosphere. So, by using this tandem type of a system, we are using a heat recovery system to further enhance the efficiency of the gas turbine. So, if we look at the gas turbine closely, it is the turbine blades which are the key components in the gas turbine which are responsible to convert the thermal energy of hot gases into mechanical energy. So, how do these blades convert the thermal energy into mechanical energy? So, here we can see this image of various series of the gas turbine blades where we can see the aerofoil shape cross section of the blade. and several blades are attached on these rotor discs as shown here and because of this aerofoil shape the hot gas is flowing over the aerofoil shaped blades generate lift because of which the blade cause rotation.

So now if we look closely at the materials and design of the turbine blades, so we understand the challenges in operation of gas turbine which include high temperature. So the high temperature strength should be there in the materials which are used to make the gas turbine. The materials which used to make the gas turbine should also have oxidation resistance because there is a strong oxidizing environment because of high temperature. The material should also exhibit creep resistance which is ability to resist deformation under constant stress and high temperature which ensures structural integrity of the gas turbines. So to find a material which has all these properties, so we have to look back at the material charts that we have seen.

So generally the metallic alloys are suitable for such applications but what happens in most of the metallic alloys, so there is a sudden loss of strength and resistance to creep with increasing temperature. So, to overcome that limitation instead of alloys super alloy materials are used in making the gas turbine blades. So, we understand that material selection for gas turbine blades will revolve around the discussion of super alloy. So, what are super alloys? So, super alloys they are also known as high performance alloys. So, that is why they have this name super attached to them.

And what are these? These are group of metallic materials which exhibit exceptional mechanical strength. They also exhibit resistance to thermal creep, deformation and they have an excellent surface stability at high temperature, means they can resist oxidation. So, superalloys they are known to maintain their strength and structural integrity at elevated temperature. Generally, this temperature can exceed 600 degree to say up to 1300 degree centigrade which is well within the service temperature range of the superalloys. Superalloys they also possess superior resistance to oxidation and corrosion even in harsh environments.

So the regular alloys that are used in other applications, they do not have this capability to resist oxidation and corrosion in harsh environments because the environment in which the gas turbine is operating is harsh. Why we call it harsh is because there is high temperature, there is high velocity gases, hot gases, oxygen is there. In all these conditions, they are perfect to cause oxidation or corrosion. Also, the superalloys they exhibit minimal deformation under prolonged exposure to high stress and temperature. So, this means the strain which is induced is minimal in the creep sort of conditions.

And because of all these characteristics, the superalloys they are able to maintain a stable and unreactive surface which is crucial for logitivity and reliability of the gas turbine. So, superalloys are also available in different types. Some superalloys which are used in gas turbines, they are nickel based superalloys. So, when we say nickel based, this means the nickel is of dominant percentage in the composition of the superalloy and nickel based superalloys are known for high temperature strength and corrosion resistance. So, other type of superalloys are also available say which are cobalt based.

So, cobalt-based superalloys they offer excellent thermal fatigue and corrosion resistance and they are often used in medical implants or cutting tools. Then there are also iron based superalloys which are typically used for industrial applications where we want to have cost effective and moderately high temperature performance required. So by concluding this short discussion we can understand for high temperature strength and corrosion it is the nickel based super alloy which is specifically used to make the gas turbine blades. So going forward we will discuss the details about nickel based super alloys and we will be skipping the discussion on cobalt and iron based because it is a nickel based super alloy which is used to make the gas turbine blade. We have talked about all the good properties about the superalloy that is they are able to retain their strength and oxidation resistance.

Now the question arises why superalloys are able to exhibit these properties of retaining strength and oxidation resistance at high temperature. So, to do that super alloys they rely on certain strengthening mechanisms which are mentioned here like solid solution strengthening, precipitate strengthening and protective oxide layer. We will understand details about strengthening of super alloys now. Solid solution strengthening includes the development of the solid solution using specific alloying elements which hinder the dislocation movement by enhancing the strength of the super alloy. In precipitate strengthening, fine precipitates are developed in the alloy microstructure which impede dislocation which further increase the strength.

And then we have certain elements added in the superalloy which are very favorable to form oxide layers and such oxide layers they render a stable surface which prevents further oxidation and corrosion. We will understand one of the mechanism in detail now. So, we know that in any material, so in any generic material if we see, so there will be lot of grain boundaries present as shown here. So, these grain boundaries are basically boundaries of where grains they solidify and there is a distinct boundary between one grain and the adjacent grain. Now what happens in super alloy, nickel based super alloy.

In nickel based super alloy, so there is nickel present which has a face centered cubic structure. So in this nickel based super alloy other than nickel predominantly aluminium and titanium are also added to form certain precipitates which take the shape of say these sort of precipitates are formed which are also known as gamma prime precipitates. Now these precipitates in the nickel base super alloy they precipitate in a very special way. So, this precipitate on the grain boundaries of the various grains in many cases. So, these precipitates may be present here.

So, we can say that. these are the grain boundaries. And on these grain boundaries, we have the gamma prime precipitates which are sitting on the grain boundaries. Now what happens, these grain boundaries they become the source of dislocation movement under loading conditions or maybe and this dislocation moment becomes more rapid because it is diffusion dependent in scenarios of elevated temperature. Now, this gamma prime precipitates are very stable at high temperature and presence of this gamma prime precipitates on the grain boundaries, this impedes the dislocation moment basically by pinning the grain boundaries. So, presence of this gamma prime precipitates it helps to pin the grain boundaries and by pinning they avoid or they impede the dislocation movement along these grain boundaries.

So, what happens? Once the grain boundary dislocation moment is impeded, so this impeding moment is manifested in form of increased strength even at elevated temperature. So in any normal alloy we do not have the presence of such precipitates like gamma prime and these are only available in super alloys in particular with nickel based super alloys and another important thing is the coherency between the nickel based matrix or the surrounding matrix which is sometimes termed as gamma and the gamma prime phases and this coherency further enhances the synchronization between the pinning precipitates and the surrounding nickel-based matrix because of which in an overall sense the nickel-based superalloys they are able to exhibit very high strength even at elevated temperatures. Then specifically these superalloys which are used in gas turbine blades and they are also cast using special casting processes to result in single crystal microstructure. What I mean by single crystal microstructure is that there are no grain boundaries. Now the question arises when there are no grain boundaries, so how do the materials solidify? So, when there are absence of grain boundaries, in that scenario, so these gamma prime precipitates they are suspended all over the microstructure in this fashion.

So, where we can say these are the gamma prime precipitates and this is the gamma matrix this gamma prime precipitates when suspended all over the microstructure of the superalloy in single crystal. So, in this case, we are discussing single crystal microstructure and here we have discussed polycrystal microstructure. So, in polycrystal it is clear now in single crystal there also the coherent precipitates can be present and the presence of this coherent precipitates may further be enhanced by subjecting the super alloy to specific heat treatment cycles and those heat treatment cycles can result in generation of more precipitates. Now what happens when these precipitates are present in the single crystal microstructure in case where there is some sort of a crack which is generated upon failure. So, when this crack encounters the presence of these coherent precipitates, so these precipitates they deflect the crack in a direction, some other direction in which it was propagating and deflection of crack results in the crack energy reduces and the further progression of the crack is arrested.

And in many cases, the crack may itself be arrested by the presence of these precipitates and we can now understand how this presence of coherent precipitates in the superalloy help to enhance their strength and oxidation resistance even at elevated temperatures. So, we can conclude that factors which enable the super alloy performance at high temperature, this include their microstructure, which is the fine-grained structure along with precipitation hardening and solid solution strengthening, which contribute to high temperature strength. Presence of alloying elements like we have discussed aluminum, nickel, cobalt, chromium, titanium, they enhance the oxidation resistance and creep resistance. And in gas turbine blades we also use protective coatings in form of thermal barrier coatings which are further useful to develop the further enhanced oxidation resistance and thermal protection of these blades. So if you look at the typical composition of any super alloy which is nickel based super alloy shown here MAR-M-247.

So the nominal weight percent composition is shown here where we will see the nickel is the dominant percentage shown by balance and all other alloying elements like the titanium, aluminium, tungsten, cobalt, chromium and their percentages are mentioned here. So there are several varieties of super alloys available which have various names. So there are series of super alloys which are Inconel based, Hask alloy, Udimet alloy, and so on. So, there are several types of super alloys which are available and each super alloy is characterized by a specific composition. So, like in Inconel we have 600 series of alloys, we have 700 series of alloys, we have 900 series of alloys.

So, all these series will have a specific nominal composition and the specific nominal composition results in some characteristic properties and based on the application the particular super alloy can be chosen to that particular application. Now, in the current lesson we are dealing with the gas turbine blades and on the right hand side we can see a typical schematic of the gas turbine where we can see an air cooled high pressure gas turbine blade how it typically looks like. We can understand that the gas turbine blade is a complex shaped component or a product which has different parts. We start from the root of the gas turbine blade which has a dovetail. This dovetail part goes into the mating dovetail part in the rotor disc.

On top of it, we have the blade platform. and on the blade platform we have the actual blade as shown here and the cross section of the blade is aerofoil as you can see and the blade it also has certain slots and holes which are known as film cooling holes present to enhance the surface area for cooling by the incoming air. So, we can understand when we have this type of a complex product and of course, which is operating in complex operating conditions of high temperature oxidation and so on. So, we have chosen a material which is known as nickel based super alloy to manufacture such blades. So, other than that, the materials which are used, popularly used in specifically gas turbine blade, they also include CM 247, RENE 80 for power generation. For the disc and casing materials, we use Udimet 720, INCO 718 which are generated using powder metallurgy.

And various coatings that is the thermal barrier coatings which are applied, they include platinum aluminide thermal barrier coatings. And here we can see the nominal composition of the RENE 80 super alloy as shown here. So now we can conclude what is the operating environment and loads which are there on the gas turbine blade. So these include all these loads centrifugal, thermal and these are basically having very steady temperatures, high temperatures. There is a lot of vibration because of a gas turbine blades they are operating at 15,000 to 25,000 rpm.

There is fatigue, there are fluctuating pressure fields, creep. mechanical stresses of the order of 80% of the ultimate tensile strength, wear is there, corrosion is there and all these complex loading environment are happening in parallel. So, it is not that one after the other rather it is everything is happening in parallel and in that scenario we have to understand what type of the gas turbine blade will be operating there. and based on this complex loading environment material selection is clear for the gas turbine which is nickel based super alloy and now going forward we will see what are the functions so gas turbine blade is basically generating power it is extracting power from the hot gases material is nickel based super alloy shape we have seen it is the three-dimensional hollow shape, Mass of one blade it is of the order of 0.3 to 1.2 kilogram with minimum section thickness of 1.5, tolerance of 0.1 millimeter or less, surface roughness of 2 micron or less and in one go maybe we are manufacturing 1000 blades with the objective to minimize the cost of manufacturing and we have a free variable of choosing the appropriate manufacturing process route. So, here just I am showing you the outline of the manufacturing processes for making the gas turbine blade which start with the investment casting process which is then coupled using specialized furnaces which are designed to develop single crystal cast. We will see details of these furnaces and methods which are coupled with investment casting, but they have the objective to make single crystal microstructure.

Then the blades are subjected to hot isostatic pressing for consolidation of the microstructure. Then blades are subjected to certain machining processes like electric discharge machining or laser beam machining to cut the holes and slots that just we have seen for increasing the surface area. Subsequently, for further enhancing the surface finish of the blade, they are subjected to creep feed grinding. And lastly, the thermal barrier coatings are applied on the blade which come in the category of tertiary manufacturing processes for the blade. So, going forward, we will be discussing details about these specific processes which result in manufacturing of the gas turbine blade.

So with this we conclude today's lesson. We will now summarize what all topics are covered. So in today's lesson we have covered the Brayton cycle that is the thermodynamic cycle on which the gas turbine blade is operating. We have looked at materials properties for gas turbine blades. We have looked at super alloy. What is a super alloy? We have looked at properties of super alloy, their applications.

We have looked in detail about the strengthening mechanism in super alloy. Then we have looked at the outline of the manufacturing processes for gas turbine blades. So, in the next lesson we will learn about details on manufacturing of gas turbine blade with casting, details about casting, how solidification of metal and alloy is different, what is the effect of cooling rate, how we can use inoculants in casting and then we will move on to the investment casting process which is specifically used to generate single crystal microstructure for the gas turbine blades.

Thank you.