

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

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**Lecture 15**

Welcome to this course on manufacturing for turbines. So in this lesson 15 of the course, we will see the thermal barrier coatings which are utilized to enhance the performance of gas turbines. So the thermal barrier coatings, these are typically applied on the blades of the gas turbine. In this lesson, we will see what are thermal barrier coatings, what material systems constitute the thermal barrier coatings what are the functions of thermal barrier coating, the role of bond coat and the failure modes of the thermal barrier coating. So as we can see in this schematic here, the thermal barrier coatings are basically refractory oxide coatings which are applied on metallic surfaces or metallic parts of the hottest zone in the gas turbine engine.

So, here we can see a typical cut section of the gas turbine engine, wherein we can see the fan here, we can see this fan from which the air is taken in. Behind this fan, we have the compressor. So, we have multistage compressor. So, we have the low pressure compressor, then we have the high pressure compressor.

Then this zone, where there are no blades this is basically the combustion chamber then we have behind the combustion chamber we have the high pressure turbine high pressure gas turbine, then behind that we have the low pressure gas turbine and as just discussed, this is the compressor. This is the axial compressor with various stages and this is the fan from where the air is sucked in. Now the thermal barrier coatings, they are only applied in the hottest zone. So hottest zone will be of course in the combustion chamber and just behind the combustion chamber the high pressure gas turbine. It is basically the hottest part.

So, these two are the hottest part of this complete engine. So, as the name of the coating is suggesting thermal barrier means these coatings they act as a barrier towards heat flow from the heat which is generated because of combustion of natural gas to the parts on which it is applied. So, specifically speaking the thermal barrier coating it is applied on the surface of the gas turbine blade, to minimize heat flow in the gas turbine blade because if heat flow will take place, so there will be the issues of creep and fatigue types of failure, which we want to avoid at all cost because in gas turbines. As we have

understood from the previous lessons that the gas turbines they are rotating at very high speed and presence of this heat deteriorates the performance of the gas turbine blades. So, this is the main objective of the thermal barrier coating and the material what constitutes this thermal barrier coating is refractory oxide.

Refractory oxide means these are oxides which have very high melting point. And to resist heat flow, we have to choose materials which are stable at high temperature as well as they have low thermal conductivity. So, these are nothing but these are ceramics. But we will see as we go forward in the lesson of this thermal barrier coating, not all ceramics are suitable to be used in the thermal barrier coating. We will understand the reasons and we will also see which materials are specifically used here in the thermal barrier coating.

And because of presence of this coatings on the blade, so heat flow is minimized in the core of the blade thereby enhancing the performance of the gas turbine. So, here we can see that how with time the degradation of a gas turbine blade it takes place and this takes place over several cycles of service and here the degradation first starts with degradation of the thermal barrier coating. So, this blade number one we can see this is an unutilized or a new blade, wherein the super alloy dovetail is shown here and then top part is also made up of super alloy. But this whitish coating which we can see here is basically the coating of the thermal barrier material.

And we can also see here the holes, sigma or pattern of the film cooling holes here as these are created using EDM or laser beam machining as discussed in the previous lessons. So these film cooling holes enhance the surface area of the blade for maximizing the heat transfer. And after several cycles of service the degradation of the thermal barrier coating it starts and as the thermal barrier coating starts to degrade, so it starts to chip chipping off of this thermal barrier coating takes place and then consequently the core of the blade is also exposed to the rigorous environment which is consisting of high velocity, high temperature gases and eventually the blade gets degraded over time. So presence of this thermal barrier coating, it not only enhances the service, it basically enhances the service length of the gas turbine blade but it also enhances the thermal efficiency of the gas turbine engine. Because thermal efficiency in gas turbine as we know depends on the temperature of the hot gases.

So, higher is the temperature of the hot gases, higher is the efficiency of the thermal efficiency of the gas turbine as specified by the Brayton cycle and to have higher temperature of the hot gases presence of thermal barrier coating is very essential. So, we will see the other details of the thermal barrier coating now. Thermal barrier coating as we can see in the current schematic this is a cut section of an aircraft engine which is based on gas turbine engine. So here different parts of the engine are shown as we have discussed this previously also, so the gas turbine in the gas turbine in the hottest zone that is the high pressure turbine the thermal barrier coating is applied and if you look at the

SEM micrograph that is scanning electron micrograph of this thermal barrier coating. So, we can see this is not just a single layer of material rather it is a multi-layer, multifunctional material which consists of a specialized material which is utilized in the thermal barrier coating which is 7 weight percent yttria stabilized zirconia.

So this is that special material or it is sometimes abbreviated as YSZ where Y is for yttria, S is stabilized, Z is zirconia and 7 weight percent of yttria is added into zirconia to stabilize it at high temperature. So as we can see in the SEM micrograph here, so the multi-layer coating of the thermal barrier material is there. So, in this we have a top coat, then we have a thermally grown oxide layer abbreviated as TGO behind which we have a bond coat and then the bond coat is basically applied on the super alloy that is the nickel based super alloy out of which the gas turbine blade is manufactured. So thermal barrier coatings are the refractory coatings of ceramic material applied on surfaces of metallic parts. This is important that thermal barrier coating these are ceramic coatings but they are applied on metallic surfaces.

So here is we can now understand the challenge that is there. It is an engineering challenge to apply a ceramic on a metal because both of the materials are fundamentally different and they behave in a different way when exposed to different type of service conditions. And the ceramic coatings are always applied or thermal barrier coating in the hottest part of the gas turbine engine which enable it to operate at high temperature. High temperature is then resulting in higher thermal efficiency. So gas turbines as we already know now are used to propel aircraft be it commercial or military or the gas turbines are also used to generate electricity whose efficiency and core power are directly related to gas temperature entering into the turbine section.

Further to increase the energy efficiency of gas turbine engines, both to increase electricity output or the thrust for jet engines. So, they further rely on improvements in the thermal barrier coating systems. So, next question arises, why thermal barrier coatings are so important? So this is data from 2010 where the gas turbine engine industry is almost equivalent to 42 billion dollars and 65% of their sales accounting for going into the jet engines and remaining going for the land-based gas turbines for power generation and as we know today that there is a more demand of air travel because of which the demand of gas turbines is increasing and subsequently there have been more discoveries of natural gas in several offshore locations to which it indicates the gas turbine engine is going to grow inevitably in coming decades. Similarly, in case of aircrafts, see as the use of gas turbines is increasing, so in the next say two decades, so to minimize the pollution, air pollution caused due to the gas turbines, so it is desired that the gas turbines, they function at more higher temperatures, so as to minimize the NO<sub>x</sub>, that is nitrogen oxide based pollutants. in the higher level atmospheric layers.

So, given all these reasons, it becomes important to understand what are the thermal barrier coatings, how they function, how they are manufactured, what materials go into making the thermal barrier coating. So, thermal barrier coating, it provides several important functions in a gas turbine. So, first important function of the thermal barrier coating is clear because of its name that is thermal barrier. So, it provides a thermal insulation to protect all the underlying parts of the superalloy. So, protecting means protecting from the high temperature because high temperatures may result into creep failure.

And if we minimize the flow of heat, so we can minimize the probability of creep failure in the gas turbine engine. Second most important function is the strain compliance to minimize the coefficient of thermal expansion. So, this point is important to understand because the TBC material it is a ceramic based material which is applied on a substrate which is nickel based super alloy which is a metallic based material. So, here what we will observe that the ceramics and metals they generally have a big difference between the coefficient of thermal expansion. So it is important that whatever material is being applied in the thermal barrier coating, the coefficient of thermal expansion should be compliant with the coefficient of thermal expansion of the underlying metallic substrate.

If there is the strain compliance is not there or if there is a mismatch between the coefficient of thermal expansion. So what is observed that the metallic based components they expand under the influence of high temperature at a faster rate compared to the or the lower coefficient of thermal expansion for ceramic based materials and this mismatch creates several defects in the thermal barrier coating and also results in the failure of the thermal barrier coating. So, strain compliance is very important for the success of thermal barrier coating on gas turbine engines. The third important point with respect to the functions of thermal barrier coating is to reflect the radiant heat from the hot gases which should be reflected away so as the heat should not reach the super alloy. Because if the heat is radiated away, so there are minimal chances of heat flow into the core of the blade and the probability of creep failure can be reduced.

Fourth point is to prolong the service life of jet engines of say 1000 hours so that they can operate at maximum operating temperature of 1300 degree Celsius especially during the takeoff and landing sequence of the flight or it can extend the service life of land-based gas turbines which are used for power generation up to 10,000 hours. So the thermal barrier coatings, they function under extreme environment and this extremity of the environment can be understood by looking at these numbers which correspond to the thermal gradient of the order of 1 degree centigrade per micron. So in 1 micron of distance here, the temperature changes by 1 degree centigrade. This is quite high, extremely high. The energy flux which the thermal barrier coating is experiencing is of the order of 1 megawatt per meter square and of course as we know the gas turbines are

operating in ambient condition, so there is a strong oxidizing environment with high speed of hot gases and this high speed is of the order of more than 1 Mach. So under such extreme conditions, the thermal barrier coating has to function and not only function and functionality is not only sticking to the substrate but also to provide the strain compliance, proper thermal insulation to the underlying super alloy parts.

So here we can see an annular section of the combustion of the thermal barrier coating where we can see the cross section of the coating using a scanning electron microscope image showing air plasma spread 7 weight percent yttria stabilized zirconia thermal barrier coating. So, next we can see how the use of thermal barrier coating has increased the allowable or maximum allowable gas temperature in the gas turbine engines. So, starting with the year 1965 when the superalloys were first invented. So, these series of superalloys which were invented were based out of UDIMIT and subsequently in conal based superalloys were developed. So, the operating temperature or the maximum gas temperature which these super alloys could function was of the order of 800 to 900 degree centigrade.

Subsequently, as the casting technology got improved and we could cast single crystal gas turbine blades, so therein we could go beyond 900 degree centigrade of gas temperature. And further improvement in the casting processes resulted in the second generation of single crystal gas turbine blades. And with application of TBC here we can see that the maximum allowable temperature it jumped from around 1000 degree centigrade to around 1200 degree centigrade which is a 200 degree increase. And further with increase of presence of film cooling holes and the TBC we could go to as high as 1400 degree centigrade. So we can say that with the use of thermal barrier coating the maximum allowable temperature has seen significant improvement in the gas turbines over the years and this is continuing to develop as more and more research goes into improving the performance of the thermal barrier coating and which will result in overall improved efficiency and performance of the gas turbine engine.

So now we will understand what is the multi-layer, multi-function nature of the thermal barrier coating? So we can say the thermal barrier coating as we have seen it is basically a multi-layer and multi-function sort of a material where we have different layers. So, the first layer here is basically the porous oxide layer. This is made up of 7% yttria stabilized zirconia. This porous layer can be manufactured using either of the two methods which are the electron beam physical vapor deposition or atmospheric plasma spraying so we will see details of these two manufacturing processes in the next lesson below this layer we have the thermally grown oxide layer then we have the bond coat and lastly this is applied on nickel waste super alloy substrate so these layers they have different values of their thickness. So, this porous layer is of the order of 0.1 to 3 millimeter. The TGO is of the order of 0.1 to 10 micron. The bond coat is of the order of thickness is of the order of

30 to 100 micrometer and the nickel will super alloy. And this substrate is of the order of 1 to 4 millimeters. So, this is basically the multi-layer.

So, there are multiple layers. Now, we will understand the multi-function, what is the function of all these layers. So, starting with the porous oxide layer, the important functions are it has the low thermal conductivity. It has high strain compliance then it is also operating under extreme temperature gradient that is of the order of 1 degree centigrade per micron. Then we have the functions of the thermally grown oxide layer also known as TGO. So, thermally grown oxide layer is an oxidation product which is created.

Once the bond coat and the porous oxide layer is exposed to high temperature and this has the large growth strain. Then bond coat is there. So, in the bond coat, it acts as the aluminum reservoir to form aluminum oxide, it is also responsible for inter-diffusion of elements between the bond coat and the nickel base super alloy. So, which elements are there? So, as we know in the nickel base super alloy, nickel is the predominant element but other than that we have aluminium which goes here into the bond coat and from the bond coat we can have other elements coming into the nickel base super alloy which include nickel, tantalum, cobalt and this movement of the elements is based on diffusion and diffusion as we know is a thermally activated process. And to activate this diffusion already we have high temperature available and it also has the capability of creep and plastic deformation and the nickel base super alloy of course this is the susceptible to creep and cyclic failure.

And we have the cooling, engine cooling air here. This can be drawn out from the vanes. This is the engine cooling air. And on the top side which is exposed to the hot gases is of course the thermal barrier coating comprising of this porous layer of 7% yttria stabilized zirconium.

So hot gases at high velocity. So this is basically the overall summary of the multi-layer and multi-function. Each layer has its own function and now we will understand how these layers they function together. So the oxide ceramic coating which is now we have just understood this is made up of 7% yttria stabilizing zirconia and then we have the metallic bonding layer or the bond coat here, and we have the nickel base super alloy. So typically these are these three layers so in the bond coat what happens during service because of the inter diffusion of the elements not only from the super alloy to the bond coat but also from the bond coat to the ceramic oxide coating. So this inter diffusion is of elements takes place because of the concentration gradient and because of which the aluminium which is a predominant element present in the bond coat it converts into alpha aluminium oxide.

So, because aluminium is much prone to oxidation because of which it converts into aluminium oxide. This alpha aluminium oxide has a special property that it is one of the slowest growing oxide layer at high temperature. And once this aluminium oxide layer is formed, it creates an impervious adherent layer with excellent mechanical integrity on the surface, thereby reducing the heat flow further to the underlying nickel based super alloy substrate. So this interconnected functionality results in the working of the thermal barrier coating. So this 7% yttria stabilized zirconia, it forms a metastable tetragonal phase which exhibits high fracture toughness due to ferroelastic mechanism which occurs at high temperature encountered in the gas turbines which is of the order of more than 3000 Kelvin.

And this reversible ferroelastic domain switching from one tetragonal variant to other, it is function once it is stressed. And this coefficient of thermal expansion of this 7 percent yttria stabilized zirconia is very similar to the coefficient of thermal expansion of the nickel waste super alloy which minimizes the strain mismatch because of the expansion under high temperature. The bond coat which is present as one of the interlayer in between, the primary function of the bond coat is to act as an aluminum reservoir which can result in formation of protective aluminum oxide maintaining cohesion with the thermal barrier coating without reacting with decomposition. It also remains elastic even at high temperature and prevents the rumbling or local separation of the thermal barrier interface. The bond coat also operate at highest temperature to minimize the amount of air used in cooling the vanes without reacting with the underlying super alloy and melting.

So, presently two material systems are used in the bond coat which include the nickel rich aluminides which have this formula MCRALY where aluminum is the predominant element and this is used to create the alpha aluminum oxide. Failure of thermal barrier coating is also important to understand because this thermally grown oxide layer is a dynamic layer. The thickness of the thermally grown oxide layer, it keeps on increasing and once it reaches the critical thickness, so then what happens, there is a rumpling action takes place which is local separation of this thermally grown oxide layer which results in release of the stored elastic energy, elastic strain energy as the film exceeds the fracture resistance. So, the stress is created at the grain boundaries of the thermally grown oxide layer and this creates a mismatch with the super alloy substrate creating the difference in thermal expansion upon cooling. So, here we can see how the thickness of the thermally grown oxide layer shown by this dark color.

So, this dark color is the TGO or thermally grown oxide layer. With increasing number of cycles we can see the thermally grown oxide layer increases and once it reaches the critical thickness so here this separation takes place which is characterized by this term rumbling of the thermal barrier coating. And once this separation takes place the failure

of the thermal barrier coating is caused because now the ceramic based oxide porous oxide layer it can get separated. So, in summary of today's lesson, we have seen the role of the thermal barrier coating in gas turbine engines. We have understood the materials which are used in the thermal barrier coating.

We have looked at multilayer and multifunction nature of thermal barrier coating. We have also looked at the materials used in various layers of thermal barrier coating and lastly we have looked at the rumpling or we can say failure of thermal barrier coating which takes place once the thermally grown oxide layer reaches a critical thickness. So, with this we come to end of this lesson. In the next lesson, we will see the manufacturing process for thermal barrier coating using two processes which is the electron beam physical vapor deposition and atmospheric plasma spray.

Thank you.