Effect of Thermal Barrier Coating in Sustainable Power production of Gas Turbines

S Ghosh, M Saha, S Bakshi and S Mondal
Mechanical Engineering Department, JIS college of Engineering, Kalyani, West Bengal 741235, India

Abstract. Gas turbine play an important role in producing power for aviation industries. A sustainable operating life with high efficiency of a gas turbine requires very high temperature operation. The increase in thermal conductivity with temperature results in high thermal stress which leads to permanent deformation reducing blade life and efficiency. A thermal barrier coating is crucial to remove such detrimental effects. In the present work, an assessment of gas turbine blade materials has been carried out to study the effect of various coating techniques to improve longevity of blades. Coating methods have been found to play an important role in determining the sustainability of gas turbine performance. It was revealed that such coatings considerably reduce the heat penetration rate and thus increase the service life of gas turbine blades.

Keywords: TBC, Gas Turbine, Coating, Sustainability, Power

1. Introduction
Gas turbine performance is improved when operating life is prolonged, operating efficiency becomes high and emissions are reduced. Design and development of the leading gas turbine blades and other engine components which are exposed to various harsh operating conditions, has been an interesting topic of research for many years. Conventionally the gas turbine blades have been manufactured using nickel, chromium, cobalt and titanium-based superalloys. However, the most suitable material has been the nickel based super alloys in the design of turbine components [1]. To improve the thermodynamic efficiency and sustainability of gas turbine power generation, increasing turbine entry temperature is highly effective. At earlier stages gas turbine engine components were manufactured from conventionally cast (CC) alloys which lacked required heat resistance. In course of time nickel based super alloys became more popular for better heat resistance and more sustainable operation [2].

Table 1 Nickel based alloys for Gas Turbine blades [3]

| Type | Alloy     | Components (weight %) |
|------|-----------|-----------------------|
|      | Ni | Cr | Co | Mo | w | Al | Ti | Ta | Nb | Hf | C | B | Zr |
| CC   | 61.5 | 16 | 8.5 | 1.75 | 2.6 | 3.4 | 3.4 | 1.75 | 0.9 | - | 0.11 | 0.01 | 0.04 |
| Rene 80 | 57 | 14 | 9 | 5 | 5 | 4 | 5 | - | - | 0.8 | 0.17 | 0.016 | 0.01 |
| DS   | 61.7 | 8.1 | 9.2 | 0.5 | 9.5 | 5.6 | 0.7 | 3.2 | - | 1.4 | 0.07 | 0.015 | 0.007 |
| CM247LC | 72.5 | 6 | 9.3 | 0.5 | .4 | 5.7 | 0.7 | 3.4 | - | 1.4 | 0.07 | 0.015 | 0.005 |
| CM186LC | 61.6 | 9.79 | 7.39 | 2 | 6 | 3.7 | 4.2 | 4.73 | 0.5 | - | - | - | - |
| SC   | Rene N4 | 71.6 | 6.4 | 6.4 | 0.1 | 5.6 | 2.9 | 0.6 | 6.4 | - | - | - | - |
| CMSX-4 | 74.4 | 2.4 | 3.3 | 0.4 | 5.3 | 5.7 | 0.2 | 8.2 | 0.08 | 0.03 | - | - | - |
| CMSX-10 | 74.4 | 2.4 | 3.3 | 0.4 | 5.3 | 5.7 | 0.2 | 8.2 | 0.08 | 0.03 | - | - | - |

To withstand the increasing operating temperature of gas turbines, directional solidification (DS) was introduced by Bridgman method where solidification slowly takes place in one direction. It removes grain boundaries which are aligned perpendicular to the stress axis. The eliminate all grain boundaries,
Pratt and Whitney used Single-crystal (SC) blade technology for JT9D-7R4 engine in 1982. This technology was useful to manufacture blades ready to operate at even high temperature compared to DS type blades. Table 1 summarizes the chemical compositions of some major alloys applicable in this perspective. At highly enhanced temperatures and harsh environments there is a tendency of core elements to get damaged if directly exposed to flame without any thermal barrier. A Thermal Barrier Coating (TBC) can be applied over those parts which get direct exposure to very high temperature in the range of 1370°C-1590°C. If a coating of low thermal conductivity is applied on gas turbine blades, there can be a possible reduction of 100°C-300°C in the associated components. On the other hand with this technology, 250°C higher combustion gas temperature can be utilized in comparison to the melting point of super alloys demonstrated earlier [2]. TBCs also increase the service life because they reduce the temperature of metal components. Fig. 1 shows a gas turbine blade before and after TBC coating. The cooling holes have enormous importance to control the blade temperature and make the whole operation sustainable.

![Figure 1. Gas Turbine Blades with cooling slots (a) without Coating (b) with TBC Coating](image)

2. Blade Life Prediction and influence of operating temperature

2.1 Analysis of Gas Turbine Blade Life

When a material is exposed to stress along with high temperature for a long time, it undergoes permanent deformation, such as creep. Creep occurs at stress less than yield stress and below melting temperature of the material. Creep deformations are responsible for mechanical degradation and eventual breakage of the materials. Thus, the estimation of creep is primary in the perspective of the reliability and sustainability of blades. Generally, Creep life prediction models uses time-temperature parameters to predict long-term creep life [4]. It uses lesser experimental data to derive the creep life prediction curve. The power law model [5,6] for steady-state creep rate $\dot{\varepsilon}_{ss}$, as a function of temperature $T$ and stress has been demonstrated in Eq. 1.

$$\dot{\varepsilon}_{ss} \propto A\sigma^n \exp \left(\frac{-Q_c}{RT}\right)$$

(1)

Where, $\sigma$ is applied stress, $A$ is proportionality constant, $Q_c$ is creep activation energy, $R$ is ideal gas constant and $n$ is the creep exponent. Larson-Miller parameter (LMP) method is widely used for predicting long-term creep life from short-term creep tests. The equation 2 depicts an empirical prediction of creep life [7] where stresses are assumed constant.

$$P_{LM} = f(\sigma) = t(C_{LM} + log t_r)$$

(2)

where, $P_{LM}$ is the Larson-Miller parameter, $C_{LM}$ is the Larson-Miller constant and $t_r$ is the rupture time for creep test. However, the model doesn’t properly explain how the deformation changes with temperature and applied stress. Newly developed models like Wilshire model and Normalized power
law [8,9] shows improved predictability of creep life where the stress is normalized with tensile strength instead of depending on yield strength.

2.2 Effect of thermal conductivity on blade life

To cope up with improving gas turbine inlet temperature towards a more sustainable power generation, manufacturing process of superalloys have experienced major developments. The operating temperature has been influenced by the melting point of nickel and cobalt in the range of 1500°C. Generally, the free electrons in a metal dictates the thermal conductivity of alloys while the same is influenced by lattice vibration in nonmetals. Easier heat dissipation and cooling of the blades need higher thermal conductivity. If the temperature distribution inside the blade is uniform, the thermal stress is reduced during operation. Various chemical compositions of superalloys greatly improve the mechanical properties. But they can cause point defects in lattice which further reduces the thermal conductivity. Figure 2 shows the trends of increasing conductivity for all type of casting samples with increasing range of temperature [10]. Such higher conductivity may result in permanent deformation in the blade profile due to higher thermal stress which an affect the life and efficiency of turbine blades. Thus, a thermal barrier coating can be fruitful to have a control over conductivity for sustainable power generation.

![Figure 2. Thermal conductivity as a function of temperature for nickel-based superalloys [10]](image)

3. Thermal Barrier Coating techniques

For protecting the gas turbine blades and associated components, a ceramic layer is plasma-sprayed over a metallic bond-coat layer which acts as a thermal barrier. TBCs primarily consists of a top coating of ceramic material that helps to block the flames to reduce heat transfer. Under the top coating there is a metal matrix called bond coating which works as a binder between top coating and the base material (Fig. 3). Primary component of the top coating is yttria-stabilized zirconia (YSZ), that is useful for protecting and insulating metallic components of gas-turbines especially in aircrafts. Bond coating consists of a layer of MCrAlY alloy that helps to prevent penetration of flame towards base material of superalloy. It is also relieves the thermal stress developed and improves corrosion resistance. Thermally grown oxide (TGO) forms when oxygen penetrates from the top coating and get...
mixed with Al component of the bond coating [11]. So, the choice of coating deposition methods must consider the high temperature properties like the heat resistance and formation of TGO.

![Figure 3. Thermal barrier coating under electron microscope [11]](image)

The mechanism and behaviour of failure for a TBC Coatings in hot and harsh environment is still not completely explored in literature. The microstructure of TBC affects oxidation resistance and coating durability which are some important performances parameters with respect to the sustainable performance of turbine blades. However, microstructure is dependent on materials used along with the methods adopted. It is crucial to analyse various deposition techniques of TBCs depending on the material and temperature used. There are three types of TBC methods: Chemical vapor deposition (CVD), Atmospheric plasma spray (APS) and Electron beam physical vapor deposition (EB-PVD). Moreover, the choice of deposition technique depends on the parameters like surface roughness requirements, coating composition and thickness as well as orientation of cooling holes. APS technique uses high-speed plasma jet consisting of He, Air and N\textsubscript{2} at ultra-high temperature for depositing the coating powder. It prevents the regeneration and early delamination of the TBC [12]. CVD is used for coating thin films of bond layer with a slow rate of deposition [13]. On the other hand, the EB-PVD method employs an electron beam in vacuum chamber to evaporate YSZ ingot, which is deposited on a preheated substrate with a thin layer of Thermally Grown Oxide (TGO). Generally, the top coatings are made using EB-PVD and APS techniques while CVD method improves the coting performance in a substantial manner. The use of TBCs can reduce the temperature as much as 300°C at the metallic surface, which improves the durability of the engine components and enhance performance. The development in aviation industries always demand higher efficiency and durability towards better sustainability in power production necessitating betterment in coating technologies.

4. Parametric effect of TBC on sustainability of gas turbine blades

4.1 Effect of change in thermal conductivity
The most important advantages of TBC coated superalloys are the lesser thermal conductivity and mechanical stability at high temperature. Presence of pores inside the material is another useful attribute towards improved blade performance. Depending on the temperature, the thermal conductivity of polycrystalline materials used as TBCs has a range of 1-30 W/m-K [13]. Among the oxides, zirconia shows very small thermal conductivity in the range of 2 W/m-K. For the YSZ with increase of yttria in zirconia, the thermal conductivity decreases by more than 50% [12]. In this way Zirconia and similar rare earths elements increase the durability of TBCs. This in turn increases the
acceptable temperature of gas turbine entry for more improvement in efficiency. A 250 μm thick coating with 4% rare earth metals like Gadolinia, Ytterbia etc. possess an approximate thermal conductivity of 0.88-1.02 W/m-K at 500°C [14]. As discussed earlier, such conductivity range acts as the biggest thermal barrier.

4.2 Effect of Coating Thickness
During the processing of TBC an adjustment must be made between the relative thickness of the top and bond Coating. The interfacial stress behaviour with the change of top coating thickness has been shown in Figure 4. It has been reported in literature that performance of thermal barrier coating improves by increasing the thickness of coating [15]. Stress generated between top coat and bond coat is also reduced with the increasing thickness. However, thick coatings cannot be applied in case of high-pressure turbine blades and nozzles due to strong centrifugal forces [16].

4.3 Effect of Cracks and Pores present in the coatings
Different types and orientations of cracks have varying effects on the performance of TBC. The presence of cracks in the top coating can lead to the failure of TBC coating. However, durability can be sometimes increased by artificially inserting vertical cracks during the coating process. Presence of these cracks reduce the chances of thermal fatigue. As the vertical crack approaches TGO, the stress intensity factor also decreases as it reduces stress concentration. Higher number of pores reduces the heat transfer to the base material by decreasing thermal conductivity of top coating. It also decreases interfacial thermal stress which is useful to improve fatigue life of TBC. But excessive pores can fail the whole coating as it can reduce the adhesion between the top and bond coating.

Figure 4. Stress variation with TBC coating thickness
4.4 Effect of coating process on mechanical properties of TBC

Figure 5 shows a microstructure comparison from Scanning Electron Microscopy (SEM) of YSZ coating cross-section, deposited using EB-PVD and laser CVD at 230 μm/h [16]. Columnar microstructures are formed in the EB-PVD process which reduces the planar modulus. Strain generation is common in this method due to the difference of thermal expansion coefficients between the base material and the ceramic top coating. CVD method is ideal for coating thin films due to very slow deposition rates. Process parameters can be optimized for non-oxides easily but for oxides appropriate selection of CVD chamber is necessary to control the rate of deposition [17, 18].

![Figure 5. Microstructure of TBC deposited by (a) EB-PVD method [16], (b) CVD method [17]](image)

For coatings of ceramic and metals of high melting point, APS based thermal spraying technique is used. In this process sprayed materials at a high speed enters the substrate resulting in high density and adhesion strength of the coating. In this process Al₂O₃ is formed during preheating, deposition and subsequent heat treatments. It plays an important role to prevent the premature delamination of TBCs. In APS process the powder forms a layered structure stacked over the superalloys. Such coatings are characterized by several pores which can reduce the thermal conductivity with temperature to as low as 0.8-1.1 W/m-K. During deposition various parameters like nozzle diameter, plasma gas power, grain size, base material temperature and roughness play an important role over final output. In Figure 6, a representative microstructure of a heat-treated APS sample shows that the topcoat is uniform with some small cracks which are not large enough to cause failure. The TGO is also observed at the interface which has two layers as discussed earlier.

![Figure 6. SEM image of a heat-treated APS TBC showing the irregular grain structure [20]](image)
5. Conclusion
A review on the performance of thermal barrier coating has been presented in the perspective of sustainable operating life. Several methods of thermal barrier coating have been analysed to assess their application areas. The study shows that TBC coating is required for protecting gas turbine blades from prolonged high-temperature operation, necessary for efficient power generation. The thermal conductivity also reduces due to the presence of pores generated in the coating process. At the same time, excessive pores deteriorate other mechanical properties. When applying on existing materials or preparing a novel coating, it is essential to select the appropriate coating process. Therefore, the development of thermal barrier coating is crucial in improving the durability of gas turbine blades leading to sustainable power generation.

References

[1] King D, Inderwildi O and Carey C 2009 Advanced aerospace materials: Past present and future Aviat. Space. Environ. 3 pp 22–27
[2] Yoo Y S 2014 Nickel base superalloys Korean J. Chem. Eng. 17 pp 1–9
[3] INCO Alloy IN-738 Technical Data The International Nickel Company Inc: New York NY USA Available online: https://www.nickelinstitute.org/media/1709/in_738alloy_preliminarydata_497_.pdf
[4] Wang Q, Yang M, Song X L, Jia J and Xiang Z 2016 Rationalization of creep data of creep-resistant steels on the basis of the new power law creep equation Met. Mater. Trans. A 47 pp 3479–87
[5] Kim W G, Yin S N, Kim S H, Ryu W S, Lee C B and Kim S J 2009 A numerical approach to determine creep constants for Time-Temperature Parametric methods Met. Mater. Int. 15 pp 559–564
[6] Abdallah Z, Perkins K and Arnold C 2018 Creep lifting models and techniques Creep p 115 IntechOpen Available from: https://www.intechopen.com/chapters/58367.
[7] Abdallah Z, Gray V, Whittaker M and Perkins K A 2014 A Critical analysis of the conventionally employed creep lifting methods Materials 7(5) pp 3371–98
[8] Kim S C, Shim J H, Jung W S and Choi Y S 2018 Short-term creep data based long-term creep life predictability for grade 92 steels and its microstructural basis Met. Mater. Int. 25 pp 713–722
[9] Whittaker M T and Harrison W 2014 Evolution of Wilshire equations for creep life prediction Mater. High Temp. 31(3) pp 233–238
[10] Zieliñska M, Yavorska M, Porêba M and Sieniawski J 2010 Thermal properties of cast nickel-based superalloys Arch. Mater. Sci. Eng. 44 pp 35–38
[11] Terada Y, Ohkubo K, Miura S, Sanchez J M and Mohri T 2003 Thermal conductivity and thermal expansion of Ir3X (X = Ti Zr Hf V Nb Ta) compounds for high-temperature applications Mater. Chem. Phys. 80 pp 385–390
[12] Wang L, Yang J, Ni J, Liu C, Zhong X, Shao F, Zhao H, Tao S and Wang Y 2016 Influence of cracks in APS-TBCs on stress around TGO during thermal cycling: A numerical simulation study Surf. Coat. Technol. 285 pp 98–112
[13] Klemens P and Gell M 1998 Thermal conductivity of thermal barrier coatings Mater. Sci. Eng. A 245 pp 143–149
[14] Craig M, Ndamka N, Wellman R and Nicholls J 2015 CMAS degradation of EB-PVD TBCs: The effect of basicity Surf. Coat. Technol. 270 pp 145-153
[15] Padture N P, Gell M and Jordan E H. 2002 Thermal barrier coatings for gas-turbine engine applications Science 296 pp 280–284
[16] Nicholls J, Lawson K, Johnstone A and Rickerby D 2002 Methods to reduce the thermal conductivity of EB-PVD TBCs Surf. Coat. Technol. 151 pp 383–391
[17] Goto T 2005 Thermal barrier coatings deposited by laser CVD Surf. Coat. Technol. 198 pp 367–371
[18] Clarke D 2003 Materials selection guidelines for low thermal conductivity thermal barrier coatings Surf. Coat. Technol. 163 pp 67–74
[19] Abedi H Salehi M Shafyei A 2018 Microstructural, mechanical and thermal shock properties of triple-layer TBCs with different thicknesses of bond coat and ceramic top coat deposited onto polyimide matrix composite *Ceram. Int.* **44** pp 6212–22

[20] Li C, Jacques S D M, Chen Y, Xiao P, Beale A M, Michiel M. di, Markossan N, Nylen P and Cernik R. J. 2016 Precise strain profile measurement as a function of depth in thermal barrier coatings using high energy synchrotron X-rays *Scripta Materialia* **113** pp 122-126