Open Access

SCHOLARENA

Journal of Material Science and Metallurgy

RESEARCH ARTICLE

Criteria for Abradable Coatings to Enhance the Performance of Gas Turbine Engines

FZ Mohammad[1*], M Mudasar[2] and A Kashif[3]

Center of Excellence in Science and Applied Technologies, Islamabad, Pakistan

[*]**Corresponding author:** FZ Mohammad, Center of Excellence in Science and Applied Technologies H-11/4, Islamabad, Pakistan, Tel: 03345344001, E-mail: hirafarooq@hotmail.com

Citation: FZ Mohammad, M Mudasar, A Kashif (2021) Criteria for Abradable Coatings to Enhance the Performance of Gas Turbine Engines. J Mate Sci Metall 2: 101

Abstract

The performance requirements of an advanced jet engine can only be achieved by reducing parasitic air flow over the tip of a rotating blade. These over tip losses can be reduced appreciably by applying abradable coatings/seals. Along with reducing leak losses abradable coatings are also useful in increasing surge margins, increasing the dimensioned tolerance level, and reducing specific fuel consumption. Abradable coatings are applied between the rotating and static components, at multiple locations, in an aero-engine. These coatings are generally bi-layer coatings comprising a bond coat and a top coat. The bond coat is meant to provide good adhesion and oxidation protection of the substrate materials while the top coat is a sacrificial layer which is meant to be abraded by the rotating element to accommodate radial growth due to temperature and centrifugal stresses. Different materials are selected for abradable coatings at different locations in an aero-engine keeping in view temperature and other operating condition in that very area. This paper presents a review on the efficacy of an abradable coating system, deposition technology, testing and qualification considerations.

Keywords: Abradable Coatings; Jet Engine; Engine Efficiency; Corrosion; Tip Clearance; Rotating Blades

Introduction

In the last two decades air traffic volume has been increased considerably whereas the total quantity of the fuel consumed has remained unchanged. This owes to an appreciable increase in engine efficiency; achieved through raising turbine inlet temperature, use of efficient aerodynamic designing and lightweight materials. Above all these areas reduction in over tip losses has played a pivotal role in increasing the efficiency of a modern aero engine [1-6]. A schematic of over tip clearance in an aero engine is shown in Figure 1.

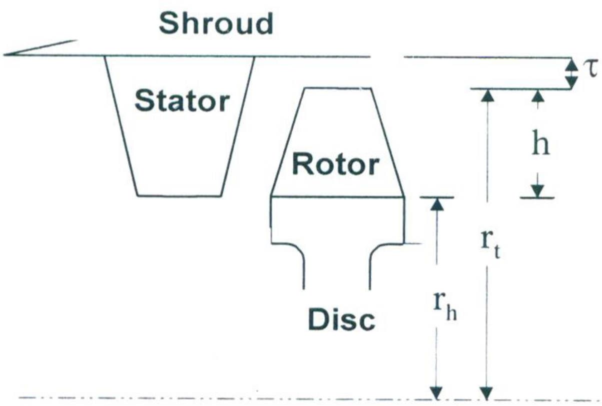

Figure 1: Schematic of over tip clearance in an aero engine [7]

Where τ is the tip clearance, h is the mean blade height from hub to tip, rh is height of disc (up to blade root) and rt is the total radius of rotor disc as shown in figure-1. Over tip parasitic losses can be reduced appreciably by applying abradable coatings [3]. These coatings are applied between the rotating and static component at multiple locations in an aero-engine. From each coating location performance increase is 0.3-1% in terms of power output [8]. Over all abradable coatings can result in 2.5% improvement in thrust and specific fuel consumption [9-11]. Potential locations of these abradable coatings in aeroengines are the housings of rotors and spool shafts in fan, compressor and turbine sections. In a typical aero-engine the locations of these abradable coatings are shown in Figure 2.

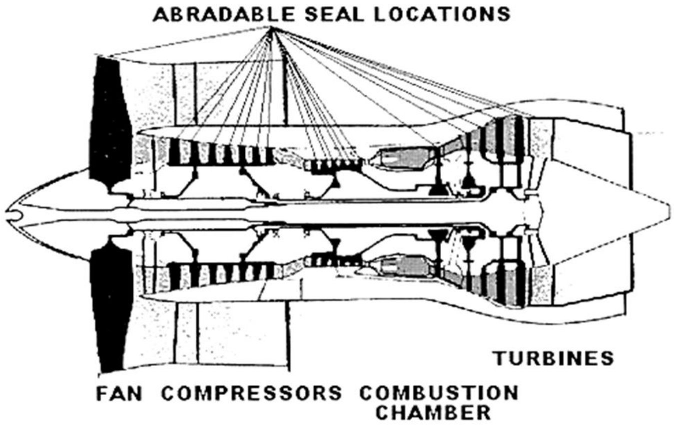

Figure 2: Location of abradable coatings in an aero-engine [12]

Abradable coatings serve following purpose in an aero-engine:

- Improve the specific fuel consumption by reducing the over tip losses.
- Increase stalls margins of an aero-engine.
- Increase manufacturing/ Assembly tolerances of engine component.
- Reduce chances of engine component damage.
- Protect metallic components from corrosion.

The tip clearance can have a major effect on the performance of a component. The degradation in performance occurs simply due to the fact that there is no work done by the rotating blade on the leakage flow (or the gas flow on the rotating element) which lowers the amount of useful work produced by the engine. A simple relation between engine efficiency and tip clearance is given in equation1:

$$\Delta\eta = -K\frac{T}{h} \tag{1}$$

Where $\Delta\eta$ = change in efficiency, K = constant, T = tip clearance, h = mean blade height from the hub to the tip [7]. This relation also shows that for smaller engine (with low blade height) this change in efficiency will be more pronounced.

Stalling is one of the major problems in an aero-engine operation. During stalling operating condition imposed upon the compressor blade depart from the design, which breakdown the air flow. This broken down air flow generates vibration and may end up in interaction between the rotor and shroud [13]. Presence of any soft material (abradable coating) between rotor and casing will restrict the damage effects [14,15] and thus increase the stall margins of any aero-engine [11].

Today turbine engine component and system design are done on computer with virtually limitless dimensional accuracy. The manufacturing world, however, does not provide for such ideal conditions. A certain amount of variation is always there [7]. Fundamentally there are two sources of these variations:

- Manufacturing variations
- Assembly variations

Manufacturing variation is largely due to the fact that there are limitations to the process used to produce a part. Assembly variations are caused by the inconsistencies in the manners in which assemblies and sub-assemblies are put together. These may include coupling alignment, assembly and tooling sequence, gravity and welding distortion and measurement error. The elimination of all possible variations is simply not possible [7]. A promising way to accommodate these variations (without affecting the component efficiency) is the use of abradable lining between housing and rotating blade, that allows self-regulation of the system by purposeful cutting of the blade tip into the relatively soft coating [11].

In an aero-engine the axial turbine clearance goal is generally 0.01-0.02 in (0.25-0.50mm). These engines are subjected to a variety of loadings. Theses loadings can cause interference between the rotating and static parts [16]. If the clearance is too small and there is no rub tolerant coating between rotor and stator, this interference will result in damage to engine parts [14]. Other causes of interferences may be deformation of the casing under operating conditions and eccentricity of rotor /stator. The presence of abradable coating between rotating and static components limits the damage [8,14,15,17]. The ceramic abradable coating; used in hot section of an aero-engine reduces the maximum metal temperature of the shroud segment by 20% [18].

Tip clearances of all turbo-machinery components vary at different points in the flight envelop. Take off condition will result in different tip clearance than cruise conditions; as shown in figure 3. The point of minimum tip clearance is immediately after the take-off when the turbine rotor is under full thermal and centrifugal loading, while the casing has not yet began to expand under the influence of temperature. At later stage of the flight casing will also heat up and expand which results in an increase in tip gap. All efforts to minimize the tip gap must be concentrated at the pinch point [7].

An ideal abradable coating system should have [14]:

- Minimum rub on rotor blades or fins- to protect the rotor blade tip sometimes it is brazed with hard particles or coated with some hard ceramic material.
- Good erosion resistance against gas and particulates.
- No material transfer from coating to the blade or blade to the coating.
- Smooth worn off surface for minimum aerodynamic loss.
- Little debris as a result of abrasion process and the released debris should not be reactive to the surface of the downstream engine components.

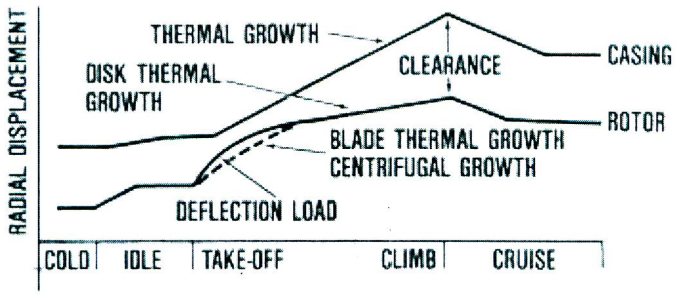

Figure 3: Take off condition will result in different tip clearance than cruise condition [7]

Abradable coatings are generally classified according to their temperature capabilities, from this criterion they fall in three categories, which are [14]:

- Low temperature abradable coatings – up to 400 °C
- Mid- range temperature abradable coatings – up to 760 °C
- High temperature abradable coatings – 760-1150 °C

Abrasion Mechanism

The wear mechanisms in abradable coatings are quite complex and include cutting, smearing, adhesive transfer of materials, crushing, melting, tribo-oxidation and erosion [15-19]. Generally, abrasion is a machining process influenced by the blade tip material, shape, tip speed, temperature and incursion rate [2]. It changes with the relative speed of the cutting blade. At high speed the removal of the coating is done by release of small particle debris (<0.1mm) and at low speed the material removal mechanism is very similar to conventional machining process [8]. A schematic of coating abrasion process is shown in figure 4. At low blade velocity the abradabilty decreases with increasing the hardness of the coating. But for similar hardness of different kind of abradable coatings abradabilty may be very different [6,15].

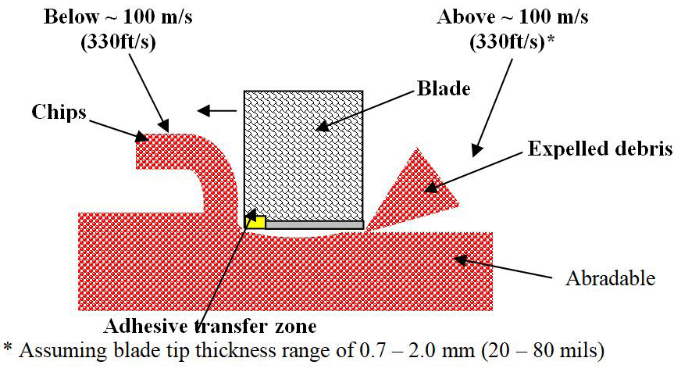

Figure 4: Schematic diagram of coating abrasion process [8]

The desired material removal mechanism for abradable coatings is fracture of bond between particles. When particle to particle contact is not broken by rub forces the resulting deformation of the structure produces an increase in heat generation within the very thin plastically deformed layer at the abradable surface. When repeated rubbing does not remove this material, further increase in densification and heat generation results in glazed surface [20].

Particles released from the abradable coating can cause numerous problems. These particles if transferred to the rotating blade can increase its mass and thus create an imbalance in the rotor. They can cause erosion of different elements of the engine [15]. This transferred material may form an alloy having a low melting point than the original constituents. The melting of these alloys produces a hard layer during the following rubbing interaction and can seriously damage the blade [15]. The transfer of abradable material to the blade is an undesirable phenomenon and it is preferable that small fragments are projected downstream when they are ejected [17,21]. The blade tip thickness plays an important role in determining behavior of the released particles, and it must be very small to allow the debris to escape to the rear, otherwise fragments will be trapped between the shroud and the tip. Generally, the blade tip thickness less than 1.3mm allows the release of particles from the coating [8].

Smearing is another problem, when it occurs the heat generation at the rub interface increase by two orders of magnitude [22], which may affect the stability of a certain coating material, and reduce the abradability, as abradabilty depends on a correlating number "N" which is

$$N = (\text{tensile strength}) * (\text{Elongation}) * \rho C_p * T_{wh} \qquad (2)$$

Where T_{wh} = hot working temperature, C_p is heat capacity at constant pressure and ρ is density [21]. The abrasion behavior of the coating also depends upon the incursion depth of the blade. For higher incursion depth the material transfer is less [21,22]. However, for low incursion depth smearing may be the problem [22]. High incursion rate also increases the maximum temperature reached during the abrasion process [15].

Abradable coatings must remain smooth with least amount of grooving, to avoid any aerodynamic loss [17, 19]. This can only be achieved if an abradable coating system has the capability to accommodate different wear mechanisms created by changing rub conditions.

The use of ceramic seals; for high temperature applications, requires hard tipping of the blade. Standard tipping system includes cubic boron nitride or silicon carbide particles embedded on blade tip [18].

To minimize problems due to removed materials, certain abradable coatings rely more on densification than on material removal. However, such an arrangement limits the functional depth of the abradable coating, since the compacted materials will increase the wear of the rotating blade tip, as the porosity is reduced [8]. Another concept is using honeycomb structure where over tip losses are reduced by the collapse of the cellular structure, when the blade rubs against them. Honeycomb structures are fabricated from sheet of selected alloys brazed together, and problem with the honeycomb seals is blade wear from the brazed joints, where thickness is two to three times higher than the cell wall thickness [22].

Materials for Abradable Coatings

Abradable coatings are applied at different locations in an aero-engine; as shown in Figure 2, the prime consideration for selecting material for specific abradable coating is the local operating temperature [23]. Form this view point temperature has become the basis for classifying abradable materials shown in Figure 5.

It is a challenge for material engineers to achieve good abradabilty in conjunction with good erosion resistance. To meet this complex combination of requirements the abradable materials consist of a composite mixture of three components; a matrix, a solid lubricant/ dislocator, and a controlled level of porosity [2,19]. Generally, coating system is comprised of a bond coat and a top coat.The composition of bond coat 95%Ni5%Al, While the composition of top coat depends upon area of engine where it is to be applied.For low pressure compressor its composition is 45%Graphite 50% Al and 5% Si. In certain applications, abradable coatings can be applied without any bond coat".

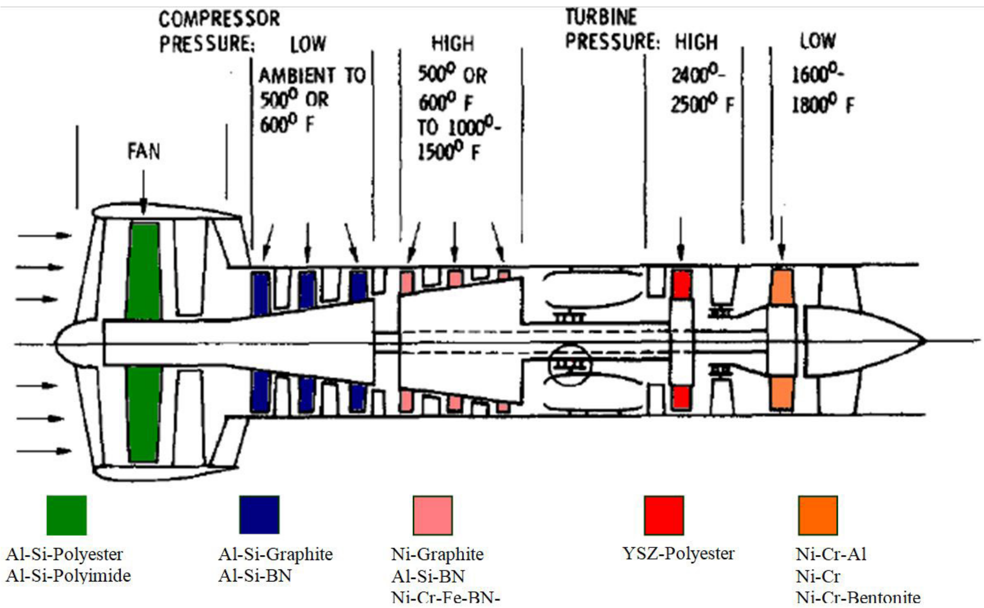

Figure 5: Classifications of abradable materials on the basis of temperature [7]

The controlled level of porosity can be produced by adding an optimized amount of polyester during spraying process [2]. Subsequent heat treatment vaporizes this polyester and leaves behind a desired level of porosity in the coating [14,24]. A typical heat treatment for this purpose is, heating the coated part at 435 °C in air [19]. The size and volume percentage of pores determines the abradabilty and erosion resistance of the coating. Typically, erosion resistance is reduced with increasing porosity level while the abradabilty characteristics of the coating are improved with increasing level of porosity [2]. Pores and voids enable the energy from the blade to be transferred to the metal matrix and fracturing the inter-particle bonds. These micro ruptures result in clean cut with minimal transfer of material to the blade body [19].

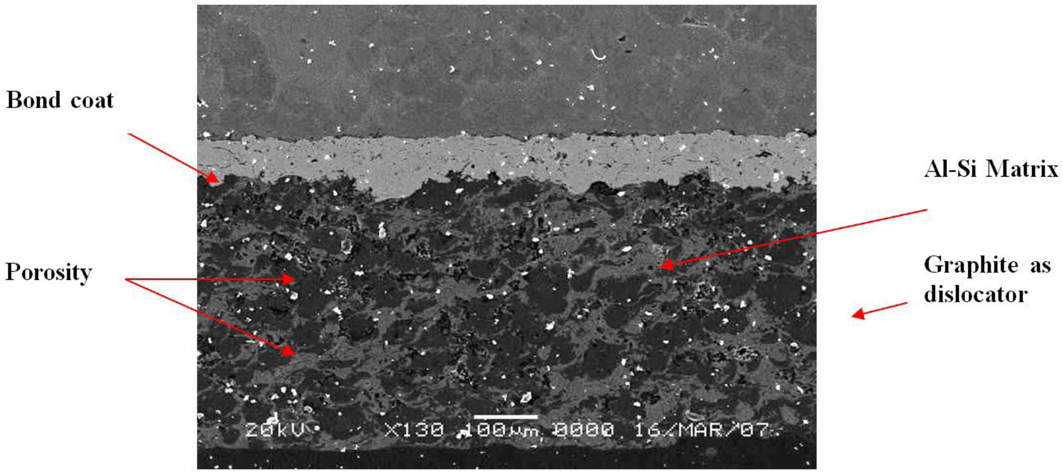

Figure 6: Components of an abradable coating system

The matrix is to provide the coating strength and resistance to environment while not resulting in excessive blade wear. The solid lubricant or dislocator phase function as an initiation and propagation route for cracks; providing the coating with an inherent weakness while ensuring abradable debris is sufficiently small that it cannot block the cooling channels or instigate erosion downstream [19,28]. Dislocators are essentially having no potential to make chemical bonding with matrix material; graphite, silicon and boron nitride are the most commonly used dislocator.

For low temperature applications two materials; polyetheretherketone (PEEK) and polyamideimde (PAI) are used very exclusively in labyrinth seals. Certain additives are added to these polymers; such as chopped carbon fiber, graphite powder or PTFE, to improve their abradabilty. High CTE of these polymers require very accurate calculation of growth with respect to the rotating components, to calculate the exact level of clearance that can be achieved [3]. PAI as labyrinth seal material may not be very useful at temperature greater than 38 °C, as PAI wears dramatically at 65 °C when it comes in contact with rotating member [3].

For moderate temperature applications; in compressor section, abradable material is composed of a metal phase, a self-lubricating non-metal phase and a controlled level of porosity. Most common materials used are Al-Si-polymer and Ni-graphite [25]. When titanium casing is used an intermediate layer of zirconia is sprayed between the bond coat and abradable coating to protect the coating against Ti-fire [14].

For temperature above 900 °C only ceramic based abradables are suitable. In order to cut ceramic based abradable coating the tip of the blade must be reinforced with well adhered abrasive grit. Technique used for this purpose is laser re-melting of blade tip with simultaneous injection of hard particles. In ceramic based abradable coatings no releasing agent/dislocators is needed because ceramics wear in a brittle manner at high temperature along with good abradabilty and erosion resistance another requirement is thermal shock resistance [18,29]. Yttria stabilized zirconia (YSZ) is the most commonly used top coat material, however dysprosium oxide (Dy_2O_3) stabilized zirconia shows a distinct advantage in cyclic life compared with YSZ [18].

Coating Deposition

The most convenient method of depositing abradable coatings is thermal spraying in which a suitable powder is heated to near or about its melting point and accelerated to the substrate and upon impact form the coating [23,25]. Almost any material that can be melted without decomposition can be deposited by thermal spraying method. Coatings produced by thermal spray process are highly anisotropic, having a layered structure. When each molten or semi-molten powder particle impacts the substrate surface or already solidified splat it produces layered structure. The shape of these individual deposits and their interaction with each other determines much of the coating properties. These deposited splats are separated from each other by inter-lamellar pores; resulting from rapid solidification, very fine voids; formed by incomplete inter-splat contact, and cracks; generated by thermal stresses. These pores, voids and cracks; as shown in the figure-7, represents the total porosity of the coating [25], and thus determines its abradabilty. Along with its wide range of applications thermal spraying makes the operation of restoration and repair of the coating very efficient; which is a critical need for aero-engine industry [26].

Thermally sprayed coatings involve two components of residual stress. The first component of the residual stress in the coating is introduced when molten powder impacts the surface of the substrate. These particles are flattened and quenched to the underlying surface temperature with very high cooling rate. During this rapid cooling the thermal contraction of the splat is constrained by the underlying material; therefore introducing a tensile stress into the sprayed material. The second component of the residual stress is due to the different thermal contraction during cooling of the sprayed coating and the substrate material to the room temperature [27].

On the basis of method used to generate the stream of molten or semi-molten particles and the deposition environment, thermal spray techniques can be classified as Flame spraying, Atmospheric Plasma Spraying (APS), and Vacuum Plasma Spraying (VPS), Detonation Gun Spraying (D-Gun), and High velocity Oxy-Fuel Spraying (HVOF).

Adhesion of the abradable coating to the substrate is an important consideration while designing an abradable coating system. Better adhesion can be achieved by depositing a bond coat between the substrate and the sacrificial top coat and by properly preparing the surface before deposition.

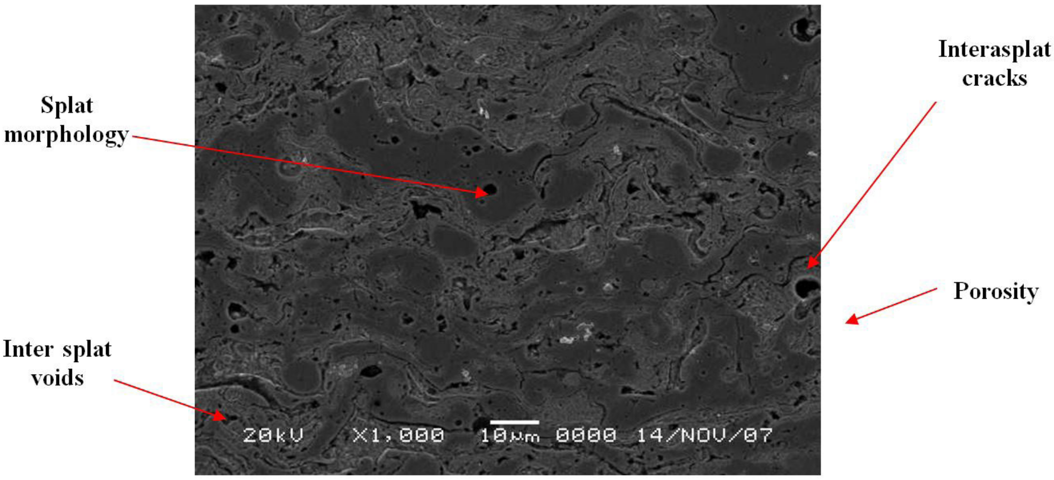

Figure 7: SEM micrograph of coating with 80Ni20Cr deposited by (APS)

Surface preparation involves grit blasting for mechanical bonding between the substrate and the coating followed by surface cleaning from dirt, dust, grease and any other foreign particles. Grit blast surface should have the same matt texture; there must be no un-blasted shiny section of the surface. Embedded grit particles can be removed by air pressure. Grit blasting media and parameters depend upon the type of the substrate material and level of surface roughness desired to be achieved.

Masking of the component should be done before grit blasting and coating deposition to prevent the component from contamination and to expose only the desired portion of the component. Masking can be done by using metallic sheets, Teflon tap, Kapton tape and silicon rubber.

Before coating deposition preheat the substrate up to 150 °C for 2-4 minutes to drive off any moisture or volatile material from the substrate. The coating should be applied within two hours of this preheating treatment. During deposition process the average temperature of the substrate should be maintained at about 200 °C. Increase in substrate temperature may cause substrate discoloration, oxidation, distortion and other conditions detrimental to the coating or base metal.

Conclusion

The efficiency of a gas turbine engine can be improved by better component design, by increasing pressure ratio, by increasing turbine inlet temperature and by reducing over tip parasitic losses. Reduction in over tip parasitic losses is one of the easiest ways to reduce the specific fuel consumption and abradable coatings have played an important role in reducing these parasitic losses. Along with reducing the SFC abradable coatings are also beneficial in increasing the stall margins of an aero-engine, giving slight leverage in dimensional tolerances of turbo components of an engine, and reducing chances of component damage due to rotor-shroud interference.

Performance of a certain abradable coating system depends upon the material composition, coating deposition technique and parameters, blade material, geometry and rotational speed. Future trends in abradable seals will focus mainly on honeycomb abradable seals because they offer some advantages over conventionally deposited abradable coatings. These advantages include good erosion resistance against gas and ingested particulates, no material transfer from seal to rotating blade, and no debris released which may affect the performance of the downstream components.

References

1. Rogerio SL (2020) Perspectives on Thermal Gradients in Porous ZrO2-7–8 wt. % Y2O3 (YSZ) Thermal Barrier Coatings (TBCs) Manufactured by Air Plasma Spray (APS), Coatings 10: 812.

2. Irissou E, Dadouche A, Lima RS (2014) Tribological Characterization of Plasma-Sprayed CoNiCrAlY-BN Abradable Coatings. J. Therm. SPRAY Technol 23: 252-61.

3. Wei Zuojun, QiaoWeiyang , Shi Peijie, Chen Pingping, Zhao Lei (2014) Tip-leakage flow loss reduction in a two-stage turbine using axisymmetric-casing contouring. Chinese J Aeronautics 27: 1111-21.

4. Batailly A, Legrand M (2015) Unilateral contact induced blade/casing vibratory interactions in impellers: Analysis for flexible casings with friction and abradable coating. J SOUND Vib 348: 344-64.

5. Sulzer M (2012) Improve Efficiency and Reduce Emissions with High Pressure Turbine Abradable Coatings for Industrial Gas Turbines.

6. Delebarre C (2014) An experimental study of the high speed interaction between a labyrinth seal and an abradable coating in a turbo-engine application. WEAR 316: 109-18.

7. Karl ES (2001) Analysis Methods to Control Performance Variability and Costs in Turbine Engine Manufacturing. MSc Thesis, May 4, 2001 Blacksburg, Virginia.

8. Ray Chupp, Farshad Ghasripoorand Gerald Moore (2012) Applying Abradable Seals to Industrial Gas Turbines, Session: AST-1: Advanced Seal Technology Session 26 Jun 2012.

9. E Irissou, A Dadouche, RS Lima (2014) Tribological Characterization of Plasma-Sprayed CoNiCrAlY-BN Abradable Coatings J thermal spray Technol 23: 252–61.

10. C Dellebare (2017) Tribological characterization of a labyrinth-abradable interaction in a turbo engine application Wear 370-371: 29-38.

11. Scrinzi E, Giovannetti L, Sheng N, Leblanc L (2014) Development of new abradable /abrasive sealing systems for clearance control in gas turbines. In proceedings of the ASME turbine blade tip technical symposium, 2013.

12. Abradable Coatings Increase Gas Turbine Engine Efficiency.

13. Structural dynamics of turbo-machines AS Rangwala.

14. Erica Scrinzi, IacopoGiovannetti, Nuo Sheng, Luc Leblanc, development of new abradable/abrasive sealing systems for clearance control in gas turbines Proceedings of the ASME 2013 Turbine Blade Tip Symposium and Course Week TBTS2013 September 30 - October 3, 2013, Hamburg, Germany.

15. Simms NJ, Norton JF, Mc Colvin G (2005) "Performance of candidate gas turbine abradable seal materials in high temperature combustion atmospheres", Materials and Corrosion 56, 765-77.

16. Rajendran R (2012) Gas turbine coatings -An overview", Engineering Failure Analysis 26: 355-69.

17. Improve efficiency and reduce emissions with high pressure turbine abradable coatings for industrial gas turbines", Sulzer Technical Bulletin 2012.

18. Scott Wilson, Oerlikon Metco, AG Wohlen (2012) Switzerland, thermally sprayed abradable coating technology for sealing in gas turbines, Thermally Sprayed Abradable Coatings 10.

19. N Fois, M Watson, MB Marshall (2016) The influence of material properties on the wear of abradable materials.

20. Guy Sutter, Sylvain Philippon, François Garcin (2006) Dynamic analysis of the interaction between an abradable material and a titanium alloy. Wear Elsevier 261: 686-92.

21. Bounazef M (2004) The Wear, Deterioration and Transformation Phenomena of Abradable Coating BN-SiAl-Bounding Organic Element, Caused by the Friction between the Blades and the Turbine Casing. Materials Letters 58: 3375.

22. Robert CB (1980) Wear of Seal Materials Used in Aircraft Propulsion Systems. Wear 59: 165.

23. Lima RS, Guerreiro BMH, Curry N, Leitner M, Körner K (2019) Environmental, Economical, and Performance Impacts of Ar-H2 and N2-H2 Plasma-Sprayed YSZTBCs. J Therm Spray Technol 29: 74-89.

24. Hardwicke CU, Lau Y (2013) Advances in Thermal Spray Coatings for Gas Turbines and Energy Generation: A Review J Therm Spray Technol 22.

25. Tanja S (2010) Process Design and Monitoring for Plasma Sprayed Abradable Coatings. J Thermal Spray Technol 564-76.

26. Erica Scrinzi, Iacopo Giovannetti, Nuo Sheng, Luc Leblanc (2013) Development of new abradable/abrasive sealing system for clearance control in gas turbines; Proceedings of the ASME 2013 Turbine Blade Tip Symposium and Course Week TBTS2013 September 30 - October 3, 2013, Hamburg, Germany.

27. Jianming Liu, Yueguang Yu, Tong Liu, Xuying Cheng, Jie Shen (2017) The Influence of Composition and Microstructure on the Abradability of Aluminum-Based Abradable Coatings. J Thermal Spray Technol 26: 1095–103.

28. Meng Zhao, Lixia Zhang, Wei Panb (2012) Properties of Yttria-Stabilized-Zirconia Based Ceramic Composite Abradable Coatings, Article in Key Engineering Materials 1551-4.

29. U Bardi, C Giolli, A Scrivani, G Rizzi, F Borgioli, et al. (2008) Development and Investigation on New Composite and Ceramic Coatings as Possible Abradable Seals. J Thermal Spray Technol 17: 805-11.