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EXPERIMENTAL STUDIES ON THERMAL PROTECTIVE COATING FOR LOW PRESSURE GAS TURBINE BLADES

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ABSTRACT

The thermal barrier coatings have many potential applications in the protection of gas turbine engine components, essentially the turbine blades. In this study micro analysis was carried out on Yitria stabilized zirconia (YSZ) coated turbine blades and the results are compared with the uncoated blades. We have used the atmosphere plasma sprayed thermal barrier coating with a thickness of 0.25 mm to withstand the high temperature of about 2000° C. A significant conclusion of the present study is that an increase in thermal coating thickness of 0.25 mm can ensure 50 % increase in the surface temperature of the turbine blades leading to a better thrust performance.

INTRODUCTION

The advances and improvements of current gas turbine technology have led to more efficient and more powerful engines. The gas temperature at the turbine entry is the most important parameter determining the specific power, specific weight, and efficiency of an aircraft. During the last two decades of research [1-10] the aero engine industry has been achieved to increase the mean mass temperature of the gas at the turbine entry from the range 1200 -1300 K to 1700 - 1800 K and the compressor pressure ratio from 20 to 30.

In this study we selected a typical aircraft for the improvement in the thermal withstanding capability of low pressure turbine (LPT) blades of its engine. The selected aircraft is a low altitude trainer aircraft having a low bypass turbo fan engine, which is used as a propulsive device for this aircraft. Reports reveal that these engines are frequently encounter defects like surge, high gas temperature in the turbine etc.. The major reasons reported from the industry for surge are foreign object damages / internal object damages, back flow due to variation in the nozzle area with respect to mass flow of air, malfunctioning of fuel accessories and engine control amplifier. Surge leads to compressor stall with increase in turbine gas temperature. High turbine gas temperature normally occurs due to surge, malfunctioning of fuel accessories and engine control amplifier. This surge and high turbine-gas-temperature (high TGT) leads to micro structural changes in the turbine blades, which further results to burn, breakage, oxidation, erosion and hot corrosion. The selected aircraft engines LPT blade materials are made up of Ni-based super alloy (Nimonic 115). Whenever engine suffering from surge or over temping, these blades undergoes damages like burn, breakage, oxidation, erosion and hot corrosion. Approximately 30 % of engines were withdrawn for above defects in which most of cases LPT blades were being rejected due to micro structural changes. In order to protect these turbine blades from high temperature oxidation and corrosion, a protective layer could be applied to overcome these problems. In general there are several ways and types to apply a protective coating on substrate. Among the different coating techniques the atmospheric arc plasma and spray paint plays an important role because it is simple, efficient and cost effective. These processes could form dense protective oxide scales. Literature review reveals that the frequent failures of LPT blades were due to various defects on engine and working conditions of engine. Till now no attempt has been made to protect these blades from failure [11]. In this paper an attempt has been made to establish a suitable protective coating for low pressure gas turbine blades for increasing its surface temperature. The experiments are carried out at the engines division of M/s Hindustan Aeronautics Limited, Bangalore, India.

EXPERIMENTAL METHODOLOGY

The experimental investigation was to develop an effective, lucrative and low energy thermal barrier coating for turbine blades in a single technological cycle. The basic procedures like abrasive blasting and cleaning are embraced for the atmospheric plasma spray coating. After spraying, the coated materials have been subjected to a series of tests, viz., micro-structural analysis of the cross sections, micro-hardness measurement, thickness measurement, porosity test, thermal conductivity analysis.

ATMOSPHERIC PLASMA SPRAY COATING

Substrate Preparation

The available aircraft engine's LPT blades were taken as the specimen for coating. The new blades are named as Category-A (CAT-A) and the serviced blades are named as Category-B (CAT-B). The CAT-A and CAT-B specimens are shown in Fig.1 and Fig.2 respectively. The selected specimens are grit blasted at a pressure of 3 kg/cm^2 using alumina grits having a grit size of 18 x 24 mesh sizes. The standoff distance in abrasive blasting is kept between 120 - 150 mm. The average roughness of the substrates is 6.8 μm. Spraying is carried out immediately after cleaning.

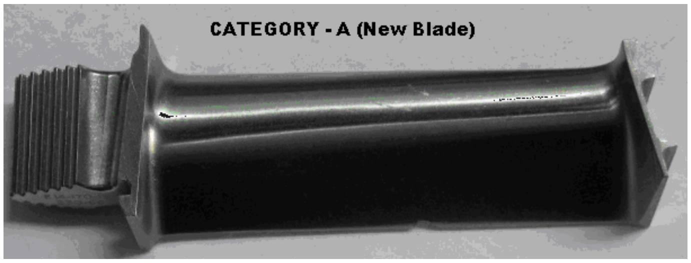

Figure 1 Uncoated CAT-A low pressure turbine blade

Figure 2 Uncoated CAT-B low pressure turbine blade

Powder Selection

Metco 204 - NS (YSZ powder) is chosen as the top coat powder. AMDRY 964 is chosen as the bond coat powder. Both this powders are kept in the heating chamber to remove the moisture before coating. The properties of the powder are given in Table 1.

Table 1 Properties of Ceramic and Bond Coating Powder

Type of Powder	Ceramic Top Coat	Bond Coating Powder
Technical Name	Metco 204 - Ns	Amdry 964
Particle Size	-125 + 11μm	- 90 + 37μm
Process	Atmosphere Plasma Spray (APS) and Vapour Plasma Spray (VPS)	APS
Chemistry	$Zro_2 8y_2 o_3$	Ni31cr11al0.6y

Masking of Blades

Masking is a process of protecting a desired area from change during production. Masking tapes used to protect portions of a work from unintended change. The masking tapes are cut as per the required size and taped to the specific portions of the materials to prevent it from changes during blasting and coating process.

Developing of Coating

Plasma spraying is a process that combines particle melting, quenching and consolidation in a single operation. The schematic diagram of the plasma spraying process is given in Fig. 3. The process involves injection of powder particles (YSZ powder and AMDRY 964) into the plasma jet created by heating an inert gas in an electric arc confined within a Water-cooled nozzle. The temperature at the core of the plasma jet is 10,000 - 15,000 K. The particles injected into the plasma jet undergo rapid melting and at the same time are accelerated. These molten droplets moving at high velocities impact on the surface of the substrate forming adherent coating.

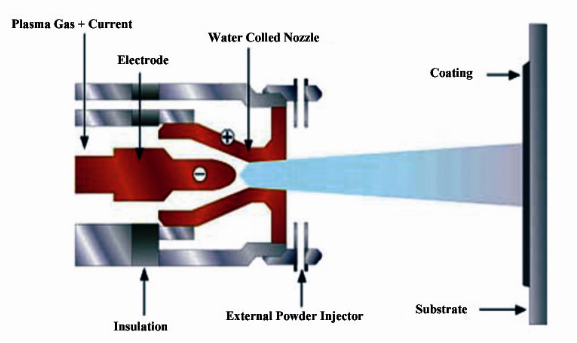

Figure 3 Schematic diagram of the plasma spraying process

The coating is incrementally built up by impact of successive particles by the process of flattening, cooling and solidification. By virtue of the high cooling rates, typically 10^5 to 10^6 K/sec., the resulting microstructures are fine-grained and homogeneous. This results in a typical lamellar structure. The coating-substrate interface bond mechanism is purely mechanical. Plasma spray deposits typically have lamellar structure with fine-grained microstructure within the lamellae.

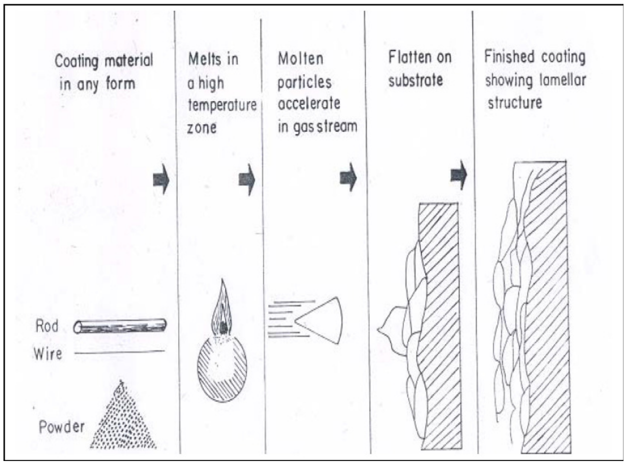

Figure 4 Schematic diagram showing steps for coating process

The complete experimental setup together with brief specifications of equipment's and methodology are done in the plasma spray system developed at the process shop has been used for plasma spray experiments. The experimental set up is shown in Figure 5. Argon is used as the primary plasma gun gas and hydrogen as the secondary gas. The powders are deposited at spraying angle of 90°. The powder feeding is external to the gun. The properties of the coatings are dependent on the spray process parameters. The operating parameters during coating deposition process are listed in Table 2. The coated samples are shown in the Fig.6 and Fig.7.

Table 2 Operating parameters during coating deposition

Operating parameters	values
Plasma Arc Current (amp)	400
Arc Voltage (volt)	40
Torch Input Power (kW)	21
Plasma Gas (Argon) Flow Rate (lpm)	20
Secondary Gas (H_2) Flow Rate (lpm)	2
Carrier Gas (Argon) Flow Rate (lpm)	7
Powder Feed Rate (gm/min)	10
Torch to Base Distance TBD (mm)	100

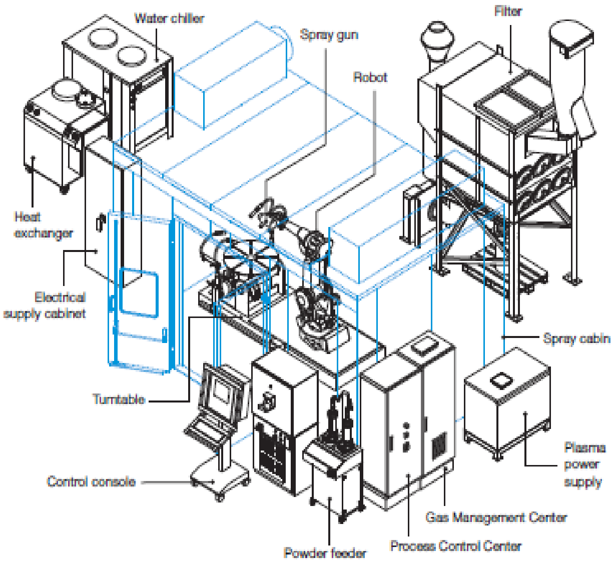

Figure 5 General Arrangement of the Plasma Spraying Equipment

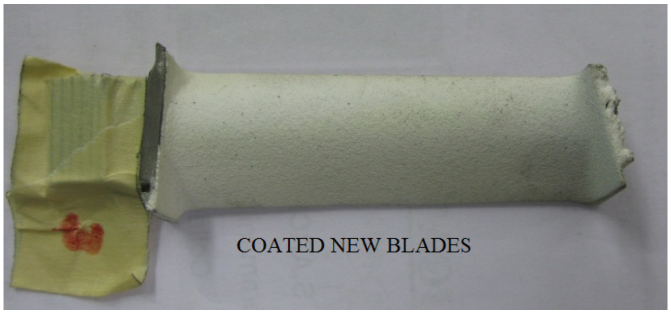

Figure 6 YSZ coated CAT-A low pressure turbine blades

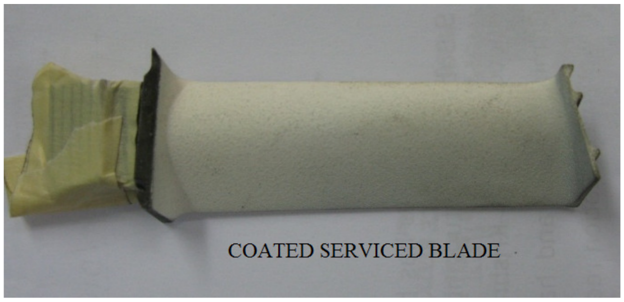

Figure 7 YSZ coated CAT-B low pressure turbine blades

MICRO STRUCTURAL ANALYSIS OF YSZ COATED BLADES

The CAT-A YSZ coated blade specimen is first placed in the optical microscope and analyzed through the optical microscope. This microstructure analysis shows that the coating was good and found satisfied the requirements of good coating properties. Both the YSZ coated blades were found satisfactory. The microstructure analyzed photos are given in Fig.8 and Fig.9.

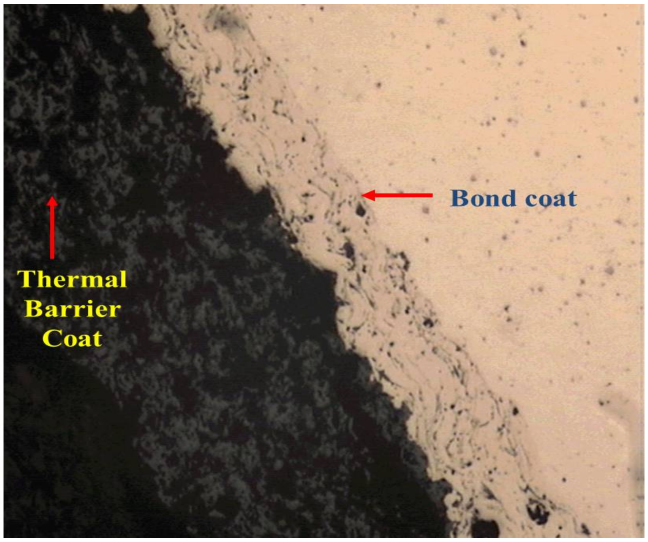

Figure 8 Microstructure of YSZ coated CAT-A blade

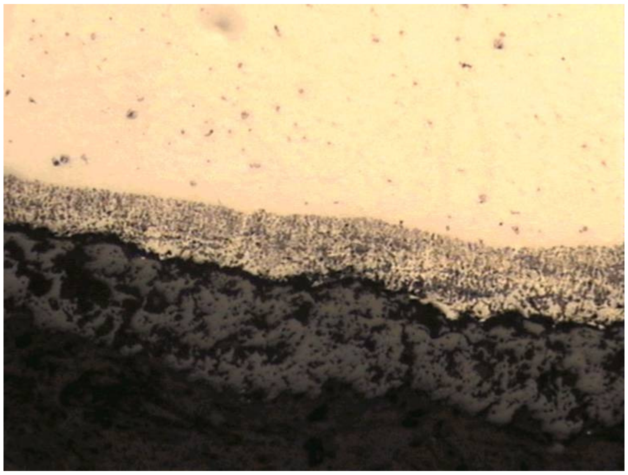

Figure 9 Microstructure of YSZ coated CAT-B blade

From the microstructure analysis carried out on both the samples, the properties of the coating are listed in Table 3.

Table 3 Properties comparison of YSZ and Sermetal coating

Properties	**YSZ coating**		**Sermetal coating**	
	CAT-A	**CAT-B**	**CAT-A**	**CAT-B**
Thermal cracks	Nil	Nil	Nil	Found
Oxidation	Nil	Only in bond coat	Nil	Found
Peeling of coat	Nil	Nil	Nil	found
Overall satisfactory condition	Satisfa-ctory	Satisfa-ctory	Satisfa-ctory	Not satisfactory

Measurement of Coating Thickness

To ensure the coat ability, coating thickness was measured on the polished cross-sections. The thickness values obtained for coatings deposited at CAT-A and CAT-B blades are presented in Table 4. Each data point is the average of at least five readings / measurements. The coating thickness is measured using image analyzer of optical microscope. The maximum coating thickness of 230 micron on topcoat and 135 micron on bond coat of CAT-A blades substrates are obtained.

Table 4 Details of coating thickness

Type of Coating	**CAT-A (microns)**		**CAT-B (microns)**	
TBC	Bond coat	Top coat	Bond coat	Top coat
	135	230	154	220

Micro hardness

Small specimens are sliced from the coated samples. Samples containing coating cross sections are mounted and polished for the micro hardness measurement. Microscopic observation under optical microscope of the polished section of the coatings exhibits three distinctly different regions/ phases namely grey, dark and spotted / mixed (see Fig.10). Vickers Micro hardness measurement is made on these optically distinguishable phases using Vickers' Micro hardness tester equipped with a monitor and a microprocessor based controller, with a load of 0.245 N and a loading time of 10 - 15 seconds. About five or more readings were taken on each sample and the average value is reported as the data point. The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136^0 between opposite faces subjected to a load of 50 kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load (F) by the square mm area of indentation (d). The hardness value is calculated by using the following formula.

$$Hardness\ Value = \frac{2\,F\,Sin(\frac{136^0}{2})}{d^2}$$

Figure 10 Micro hardness test on YSZ coating

The average hardness values obtained from four readings for bond coat and top coat are 400 and 257 respectively.

Porosity

The porosity of the coatings was measured by putting polished cross sections of the coating sample under a microscope equipped with a CCD camera. The digitized image is transmitted to a computer equipped with Visual Optical Imaging System (VOIS) analysis software. The total area captured by the objective of the microscope or a fraction thereof can be accurately measured by the software. Hence the total area and the area covered by the pores are separately measured and the porosity of the surface under examination is determined. The porosity of the bond coat is constant of about 1 %. The porosity of the top ceramic coat varies from region to region, thus the porosity range of the YSZ top coat varies from 8 % to 13 % (see Fig.11). From the literature we got the graphical change in the thermal conductivity of the coating based on the porosity level of the coating. If the porosity of the coating is low then the thermal conductivity of the coating is high. In addition, a higher porosity level causes a decrease in the thermal conductivity of the coating. So to get low thermal conductivity, we want high porosity but there is a limit in the porosity level. In our coating the porosity level is maintained

Figure 11 VOIS image to find porosity

within the limits to get the low thermal conductivity coating. Using the basic heat transfer equation we have found that to reduce the temperature by 50 % we need coating thickness of about 0.256 mm. We also made an attempt to calculate the temperature at different regions, which is shown in Fig.12. Using the available data, we made an attempt to calculate the specific thrust of a turbo fan engine. We found that by implementing the thermal barrier coat (TBC) on the selected turbo fan engine, one can increase about 50 % of the overall engine thrust [11].

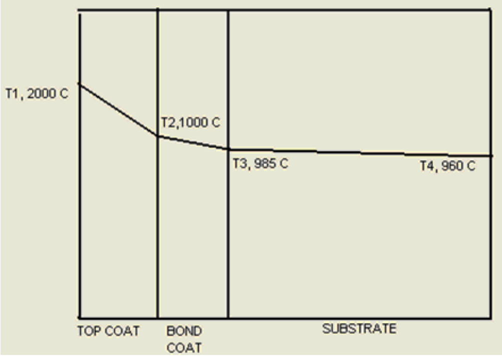

Figure 12 Predicted temperature distribution.

CONCLUDING REMARKS

We have conjectured through the experimental studies on thermal protective coatings for low pressure turbine blades of a turbofan engine that the thermal barrier coating diffused to the low pressure turbine blades provided a satisfactory adhesion to the new blades (Category – A) as well as serviced blades (Category – B). We inferred that the thermal barrier coating has very low thermal conductivity and thus the high gas temperature in the turbine seldom causes any adverse effect. The porosity of our Yttrium Stabilized Zirconia thermal barrier coating by Atmosphere Plasma Spray process was within the range of limit (8 - 13 %). We inferred that the range of porosity gives the low thermal conductivity property of about 0.6 W/m K because the pores are parallel to the substrate. A significant conclusion of the present study is that an increase in thermal coating thickness of 0.25 mm can ensure 50 % increase in the surface temperature of the turbine blades. Thus the thrust of the selected trainer aircraft engine is found increased to 83 KN. Through our preliminary theoretical analysis we found that the coated blades can withstand the high temperature of about 2000° C for a period of approximately one hundred hours and the thrust of the engine can be significantly increased. We further concluded that the implementation of the thermal barrier coatings on low pressure turbine blades can protect the temperature shoot-ups and can save the periodic replacement cost. And the serviced blades can be lucratively reused in the aircraft engines without altering the engine design parameters.

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REFERENCES

[1] Tamarin Y., Protective coating for turbine blades, *ASM International*, Materials Park, OH 44073–0002, USA, ISBN: 0–87170–759–4, 2002.

[2] Mishra S.B., Prakash S., Chandra K., Characterisation of plasma sprayed NiCrAlY, Ni-20Cr and Ni3Al coatings on a Ni-based super alloy Inconel 718, Department of Metallurgical & Materials Engineering, Indian Institute of Technology Roorkee, India, 2004.

[3] Sudhangshu Bose, and Jeanine DeMasi – Marcin, Thermal barrier coating experience in gas turbine engine at Pratt & Whitney, East Hartford, Connecticut, *Journal of Thermal Spray Technology,* Vol.6, March 1997.

[4] Hetmańczyk M and Swadźba L., Mendala B., Advanced materials and protective coatings in aero-engines application, Department of Materials Science and Metallurgy, Silesian University of Technology, Poland. Vol.24, Issue 1, September 2007.

[5] Misbahul Amin.M., *Oxidation Behaviour of IN-738 LC Super alloys in the Presence of Ionic Salts at 1173 K,* Department of Chemistry, Faculty of Science & Technology, University College of Science & Technology Malaysia, Malaysia. November 2003.

[6] Vitalii Postolenko, Failure Mechanisms of Thermal Barrier Coatings for High Temperature Gas Turbine Components under Cyclic Thermal Loading*, Ph.D Dissertation*, Aus Kiew, Ukraine, November 2008.

[7] Asok Kumar N., Kale S.R., Numerical simulation of steady state heat transfer in a Ceramic-coated gas turbine blade, *International Journal of Heat and Mass Transfer* 45 (2002) 4831-4845.

[8] Antonio Licciulli, Thermal barrier coatings for aeronautic engines turbine blades*", Science Technology of Ceramic Materials*, 2002.

[9] Botto D., Martena M., Saddadini S., Numerical model of a TBC system stress distribution as a function TGO thickness and thermal expansion mismatch, *XXXIII Convegno Nazionale dell'Associazione Italiana per l'Analisi delle Sollecitazioni*, 31 August - 2 September, 2004.

[10] Wahl, G., Ch. Metz, and Samoilenkov S., Thermal barrier coatings, *Proceedings of Thirteenth European Conference on Chemical Vapor Deposition*, EDP Sciences, Les Ulis, France, 2001.

[11] Vinoth Kumar A., Vijay Anand M., Jerish Duthie J., and Archana S., Analyzing and establishing the protective coating for low pressure turbine blades of Adour MK811 engine, *Project Report, Bachelor of Engineering*, Department of Aeronautical Engineering, Kumaraguru College of Technology, Coimbatore-49, India, April 2011.