Novel Thermal Barrier Coatings Produced by Axial Suspension Plasma Spray

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ABSTRACT

Ceramic Thermal Barrier Coatings (TBCs) on superalloy components are being used successfully in land-based gas turbine and aircraft engines. These coatings are generally made by either air plasma spraying (APS) or electron beam physical vapour deposition (EB-PVD). In general, EB-PVD TBCs have superior durability due to the columnar structure, but they are very expensive compared to APS TBCs. EB-PVD TBCs are used primarily in the most severe applications such as turbine blades and vanes in aircraft engines. This paper presents an economical process to make durable TBCs, called Axial Suspension Plasma Spray (ASPS). This technology combines Mettech's axial injection plasma process and automatic suspension feed system. The resulting TBCs exhibit columnar structures with vertical cracks, similar to EB-PVD coatings. Such structures allow the TBC to compensate for thermal expansion differences between it and the base material. The ASPS process presents an economical alternative to EB-PVD to produce durable columnar TBCs.

1 Introduction

Thermal barrier coatings (TBCs) have been employed for many years to protect the metallic components of the hot sections of aerospace and land-based gas turbines against the high temperature environment. A typical TBC consists of two key layers: an oxidation resistant bond coat such as diffusion aluminide or MCrAlY coating, and a ceramic top layer, typically 7-8 weight% Y_2O_3-stabilized ZrO_2, to reduce the heat flux into the component. The typical thicknesses of TBCs vary between 100 and 500 μm, and they can provide a major reduction in the surface temperature of the metallic components of up to 300 °C when combined with the use of internal air cooling of the underlying metallic component. Therefore, TBCs enable an increase in the efficiency and performance, and a reduction in the pollution levels of these engines [1,2].

The top ceramic coating is usually applied either by air plasma spray (APS) or electron-beam physical vapour deposition (EB-PVD) process. Although EB-PVD process offers better coating mechanical properties due to the presence of columnar structure, its application is limited to critical turbine components such as first stage of rotor blades due to the disproportionately high cost and low deposition rate. Plasma spraying is, in contrast, a more cost effective process with higher deposition rate and wider composition flexibility than EB-PVD process [3]. Two important targets of new TBC development are property improvement and cost reduction.

Mettech developed an industry-ready process called Axial Suspension Plasma Spray (ASPS) [4] to solve the problem of delivering sub-micron size particle to a plasma torch for production of novel coatings. This technology combines Mettech's axial injection plasma process and automatic suspension feed system. By suspending fine powders in liquid and injecting the fine powder suspension into the plasma plume axially, a reliable delivery mechanism to spray fine particles is obtained, and this technology has demonstrated capability to deliver consistent quality coatings for different applications [5, 6]. This paper presents a novel process to make economical columnar TBCs using ASPS technology.

2 Experimental

The coatings were applied using the Axial III™ plasma torch with a modified injector for suspension atomization and the NanoFeed™ suspension feeder, (Northwest Mettech Corp., North Vancouver, Canada). The Axial III™ injects the atomized suspension feedstock axially to the direction of spray into the central core of the plasma. Axial injection overcomes the injection difficulties that arise when attempting to penetrate the plasma radially with fine particles or droplets. The NanoFeed is designed to feed submicron suspensions using mass flow control of both suspension and atomizing gas to provide uniform atomizing dynamics at the injector. An overview of the ASPS process is shown in Fig. 1.

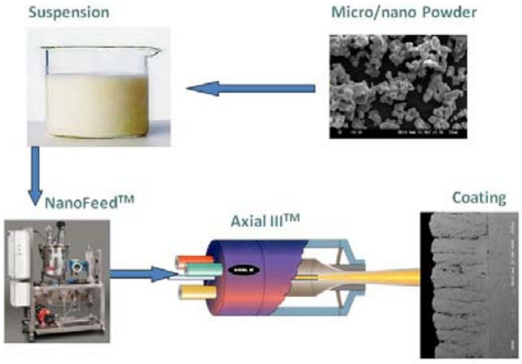

Fig. 1 ASPS process overview

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Deposition was carried out onto sandblasted INC718 substrates. Typical plasma parameters with a power level of 90kW were optimized for TBCs. A submicron yttria stabilized zirconia (8YSZ) powder was used in the preparation of the suspension. The surface and cross section of the coatings were examined by optical microscopy (OM), X-ray diffraction (XRD) and scanning electron microscopy(SEM).

3 Results

3.1 Columnar Structures

The structure of a typical ASPS coating optimized for TBC is shown in Figs. 2 and 3. Compared to other APS coatings, this structure shows a distinct difference. The coating surface is broccoli-like, which is typical for columnar structure. The coating density is above 90% within the columns, while between the columns the density is around 60%. A high magnification of structure (Fig. 3c) discloses that the coating doesn't have the typical splat structure with flattened particles; instead, the grain is substantially equiaxed with submicron scale porosity. The width of the column is in the range of 20-50 μm, which is larger than that of most EB-PVD column widths [3]. The columns impart strain tolerance to the TBC because they can separate at high temperatures, accommodating CTE stresses, thus producing excellent durability like EB-PVD TBCs.

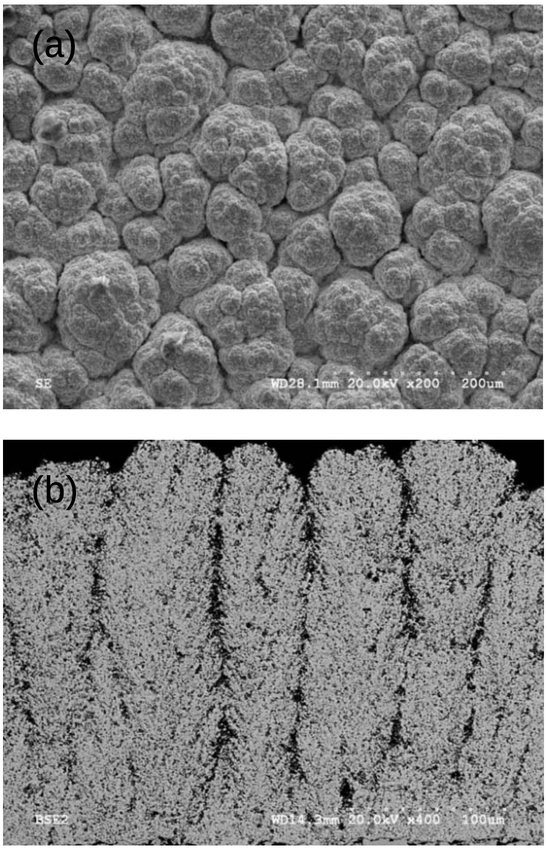

Fig. 2. Columnar TBCs by ASPS, (a) surface morphology, (b)polished cross section

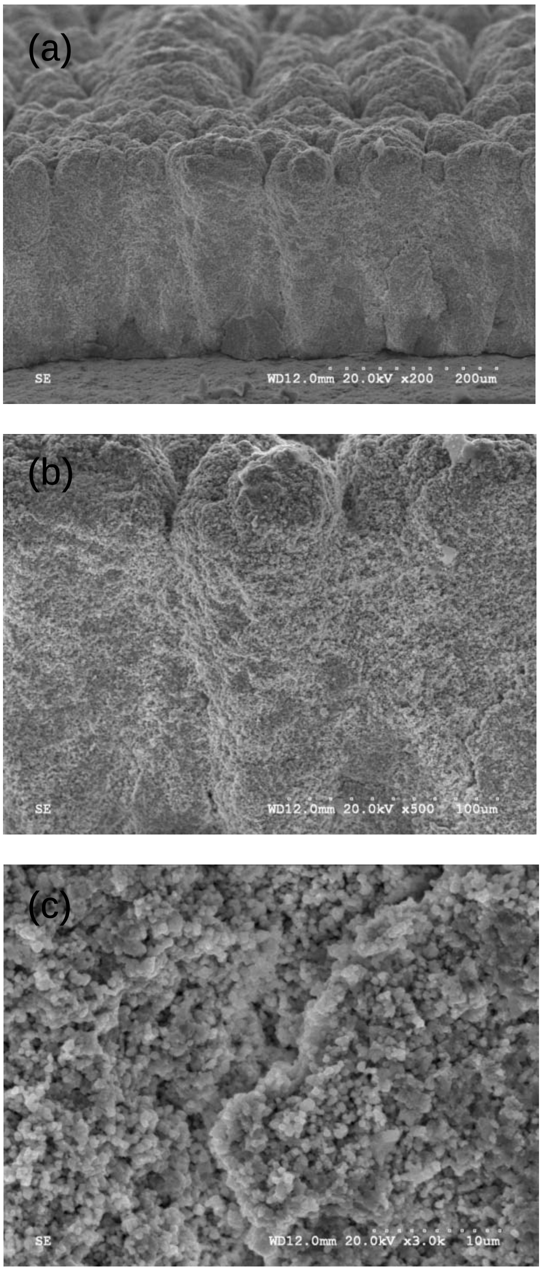

Fig.3 Fractured cross section of ASPS TBCs with different magnification, (a) 200x, (b) 500x and (c) 2000x

3.2 Coating phases

Fig. 4 shows the XRD spectra of the YSZ powder used, and the resulting ASPS coating. Even though the powder has a little monoclinic phase, the coatings are primarily t' tetragonal with no indication of monoclinic phases, which is the most desired phase for TBC applications.

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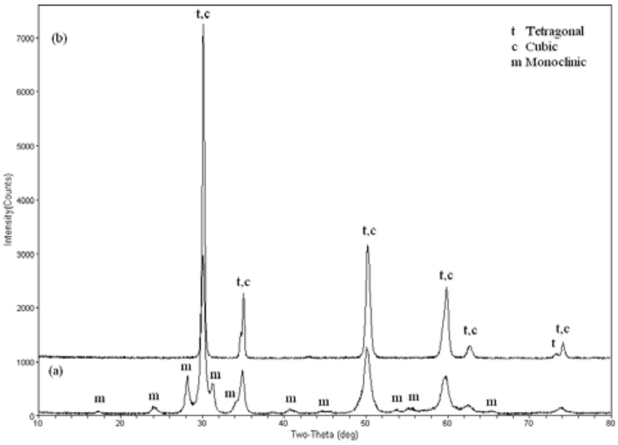

Fig. 4 XRD spectra of YSZ powder and ASPS coatings, (a) As received powder, (b) ASPS TBC

3.3 Coating performance

A TBC system includes a superalloy substrate, metallic bond coat and ceramic top coats. The performance of TBC system is related to the design of the TBC system, and its operating environments, which is different for different hot section parts and engines. Mettech has applied ASPS TBCs on a variety of substrates including MCrAlY bond coat, and diffusion Al and PtAl coatings. The coating properties, combined with the data from SURFTEC reports [7, 8], were summarized in Table 1 and compared to APS and EB-PVD data referenced from literature [2, 3]. The bond strength and thermal conductivity of ASPS TBCs are in the same range as that of EB-PVD TBCs. It is reasonable to conclude that the thermal conductivity of ASPS TBCs is higher than that of APS TBCs, as the column boundary serves as channels for heat flow. It is interesting to note that bond strength of the ASPS TBCs is significantly higher than that of traditional APS TBCs, even on smooth bond coat surface. This is a high merit for TBC applications as a smoother bond coat surface will reduce the out of plane stress, which is the primarily cause for TBC spallation and failure. From these properties it is believed the ASPS TBCs could be a potential alternative to EB-PVD TBCs.

Table 1 Summarized ASPS TBC Properties

Properties	*APS*	*ASPS*	*EB-PVD*
Bond Strength, MPa	20-40	50-82	65-75
Thermal Conductivity, W/mK	0.9-1.5	1-2	1.7-2

3.4 Effect of key variables on coating structures

The targeted application for ASPS TBCs is on rotating blades and high-pressure turbine section vanes, which have complex shapes. A broad processing window is necessary to get uniform coatings on the entire airfoil surface. Among the process parameters, the key processing variables for this application are stand-off distance (SOD) and spraying angle. The bond coat surface roughness could be very different depending on the bond coat type and process. In addition, TBC is used in combination with internal air cooling of the metallic components. Cooling holes perforate the surface of many parts and the holes need to be clog free, which is an issue of most spraying processes.

Fig. 5 shows ASPS TBCs on two surface roughness, which are corresponding to aluminde coatings (lower roughness, Ra 1.4 μm), and MCrAlY bond coats (higher roughness, Ra 3.8 μm). Columnar structures are formed on both rough and smooth surfaces. However, the coating on rougher surface are denser and with wider columns.

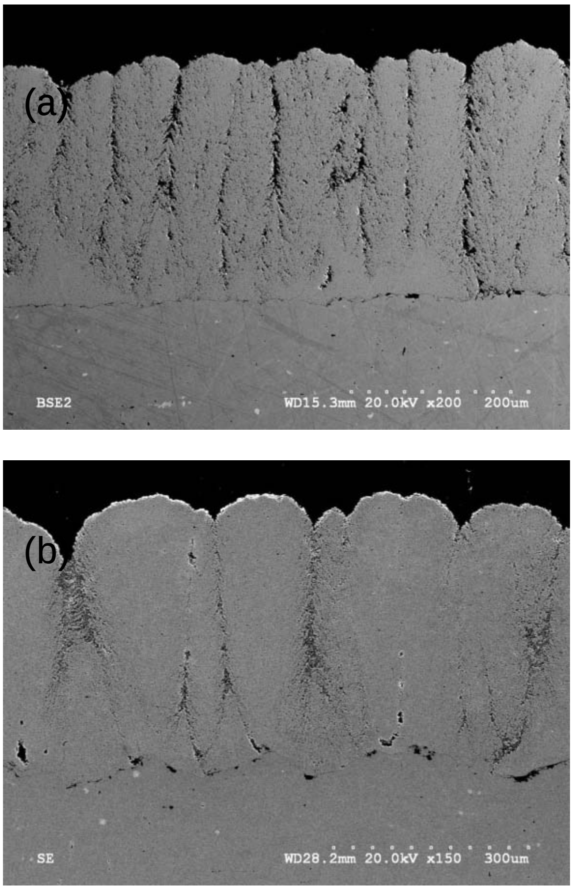

Fig. 5 ASPS TBC on bond coat with different roughness Ra (a) 1.4 μm, (b) 3.8 μm

Fig. 6 shows ASPS TBCs sprayed with longer and shorter than standard SOD (75 mm). At a SOD of 50 mm, the coating is dense and exhibits columnar structures mixed with some vertical cracks. The dense, vertically segmented structure is also favoured for TBC as it provides tolerance of the ceramic layer to the strain caused by the coefficient of thermal expansion (CTE) mismatch of the ceramic and bond coat. At a longer SOD of 100mm, the coating is columnar structured but much more porous.

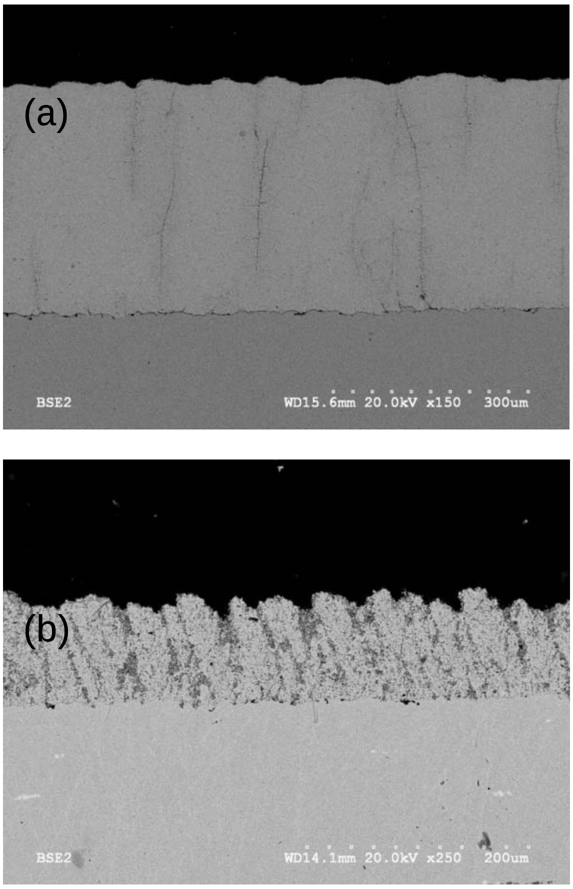

Fig. 6 ASPS TBC sprayed with different stand-off distance, (a) 50 mm, (b) 100mm

Columns grow perpendicular to the substrate surface in coatings sprayed at 90°. When spraying off perpendicular, the coatings still show good columnar structure, but the columns grow at an angle. Figure 7 shows the coatings sprayed at 45°. It appears as though the columns grow toward the plasma plume, no matter what the spraying angle is.

To investigate the impact the coating has on airfoil cooling holes, a substrate with a hole of diameter of 0.5 mm was sprayed producing a 250 μm thick coating. Fig. 8 shows the hole remains open, but becomes slightly restricted. After removing the coating, it can be seen that the coating thickness within the hole is around 25 μm.

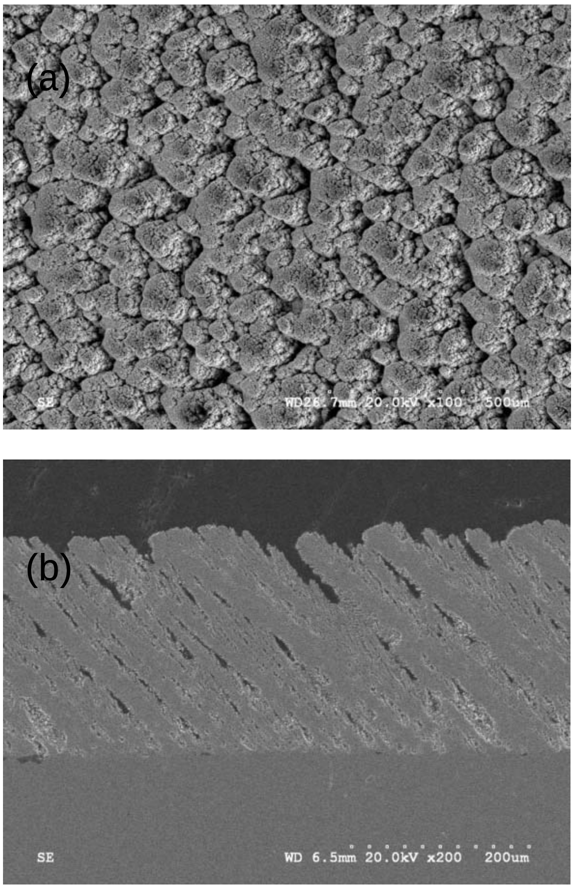

Fig. 7 ASPS TBC sprayed at 45°, (a) surface morphology, (b) cross section

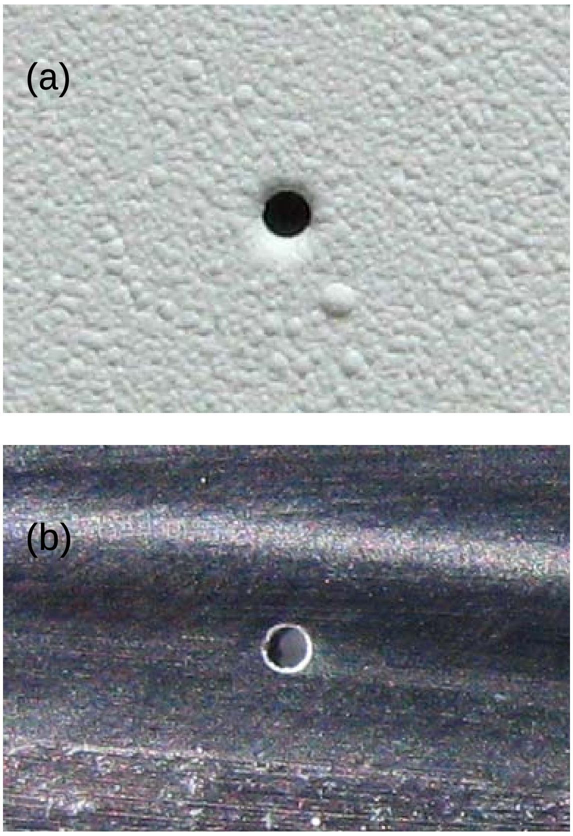

Fig. 8 ASPS TBCs around the cooling hole, (a) after spraying, (b) after removing the coating

3.5 Coating on parts

A turbine blade was sprayed with ASPS to produce a TBC. As shown in Fig. 9, a uniform and well adherent coating was produced on the whole surface. Furthermore, the blade was cut and polished to investigate the cross section microstructure. It is found that good columnar structure was formed on both the concave and convex faces as shown in Fig. 10. The coatings on the leading edge and trailing edge are denser and exhibit a mixture of columns and vertical cracks, which corresponds to a shorter SOD.

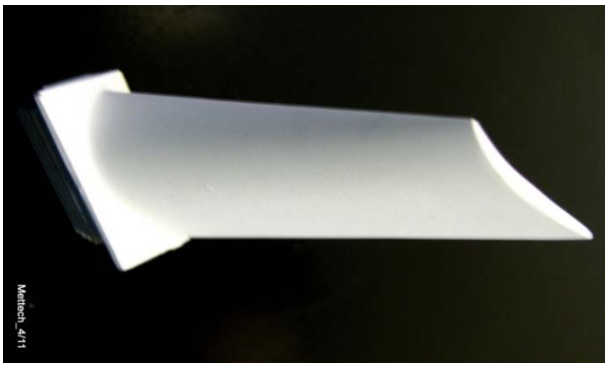

Fig. 9 Picture of ASPS-TBC coated blade

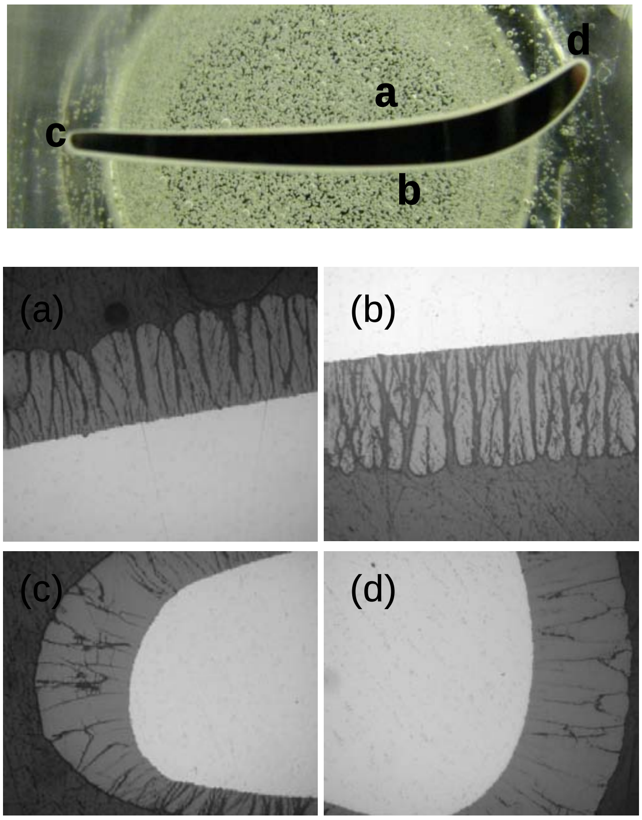

Fig. 10 Cross section of coatings on blades at different locations (a) concave surface, (b) convex surface, (c) trailing edge, (d) leading edge

4 Summary

1) ASPS TBCs exhibit a columnar structure with substantially equiaxed grains, instead of the typical lamellar structure with flattened particles for APS TBCs. Such structures allow the TBC to compensate for thermal expansion differences between it and the base material, resulting in excellent durability.

2) The bond strength and thermal conductivity of ASPS TBCs are in the same range as of EB-PVD TBCs. Particularly the bond strength of the ASPS TBCs is significantly higher than that of traditional APS TBCs, even on smooth bond coat surface.

3) Columnar structures can be achieved within the range of a few key variables: SODs from 50 to100mm, spraying angles from 45° to 90°, and bond coat surface roughness's from 1.4-3.8μm. A uniform and well adhering coating was obtained onto the whole turbine blade surface.

4) The ASPS process presents a significant potential to replace EB-PVD for aircraft turbine parts and offers an economical method to deposit durable columnar TBCs.

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