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Microscopic observation of laser glazed yttria-stabilized zirconia coatings

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ABSTRACT

Thermal barrier coatings (TBCs) are frequently used as insulation system for hot components in gas-turbine, combustors and power plant industries. The corrosive gases which come from combustion of low grade fuels can penetrate into the TBCs and reach the metallic components and bond coat and cause hot corrosion and erosion damage. Glazing the top coat by laser beam is advanced approach to seal TBCs surface. The laser beam has the advantage of forming a dense thin layer composed of micrograins. Plasma-sprayed yttria-stabilized zirconia (YSZ) coating was glazed with Nd-YAG laser at different operating conditions. The surface morphologies, before and after laser treatment, were investigated by scanning electron microscopy. Laser beam assisted the densification of the surface by remelting a thin layer of the exposed surface. The laser glazing converted the rough surface of TBCs into smooth micron-size grains with size of 2–9 μm and narrow grain boundaries. The glazed surfaces showed higher Vickers hardness compared to as-sprayed coatings. The results revealed that the hardness increases as the grain size decreases.

1. Introduction

Yttria-stabilized zirconia (YSZ) is a ceramic thermal barrier coating that has come of age in high temperature application industries. Thermal barrier coatings (TBCs) have been developed to improve the efficiency of high temperature components in various gas turbines for aircraft propulsion, power generation, and marine propulsion, among the principal ones [1–7]. TBCs offer protection for underline metallic components from creep, oxidation and/or localized melting by insulating the metal from hot gases in the engine core. The state-of-the-art aerospace TBCs typically comprise yttria-stabilized zirconia (YSZ) ceramic coat over a NiCrAlY superalloy bond coat. Yttria-stabilized zirconia (YSZ) coat has low thermal conductivity (2 W/m K for bulk and 1.5–2.05 for plasma-sprayed YSZ) and remains stable at high operating temperatures [8]. The bond coat is usually *M*CrAlY (*M*: Ni, Co or NiCo) layers deposited by vacuum plasma spraying (VPS) and high velocity oxy-fuel (HVOF) [9]. During service at elevated temperatures, oxygen transported through the top coat by diffusion through the connected porosity or ionic conduction causes the bond coat to oxidize, primarily forming Al_2O_3. This is usually termed the thermally grown oxide (TGO). Formation and thickening of this layer may contribute to TBCs failure [10–16].

Some studies focused on sealing the porosity in plasma-sprayed ZrO_2-based ceramic coatings by laser surface glazing [17–25] and laser cladding [26], which produces a combination of a porous coating with a fully dense top layer. Laser treatment is usually associated with the propagation of cracks. Cracks in the ceramic layer parallel to the surface are very detrimental to TBC lifetime because of spallation, but vertical cracks are generally considered to be beneficial to accommodate the strain occurring during thermal cycling [27]. It was shown that the vertical cracks in coatings induced by laser treatment improved the thermal shock resistance [18,19,22]. Coatings resulting from in-situ laser remelting present a columnar dendritic structure, which is closed to the vertically segmented microstructure deriving from the electron beam-physical vapor deposition (EBPVD). So, in comparison to the lamellar structure resulting from thermal spray, the columnar structure probably permits a better thermomechanical resistance during thermal cycling [28]. Miller and Berndt [29] showed that laser glazing prevented the surface spalling of TBCs subjected to a high heat flux environment. Another study reported that laser glazing increased the thermal shock resistance of TBCs in diesel simulating conditions up to 900 °C [30].

In hot gases environment, the penetration of sulfur, sodium and vanadium contaminants contained in many industrial low-quality fuels through the porous and microcracked TBCs may attack the underlying metallic components by hot corrosion mechanisms [31–33]. Hot corrosion results from the presence of salt contaminants such as Na_2SO_4, NaCl and V_2O_5 which form molten deposits that react with the protective oxide coatings [34,35]. Laser glazing is an approach to improve the hot corrosion resistance of zirconia-

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based thermal barrier coatings by preventing salt penetration into the coating [31,32]. This provides a remelting and subsequent solidification of a dense top layer with a new microstructure and less surface roughness, free from porosity but with formation of crack networks perpendicular to the surface [28,36–38].

Laser glazing improved the durability of TBCs because the segmented cracks that occurred during glazing are beneficial for accommodating thermal stress and raising the tolerance to oxidation, which resulted in a higher durability [39]. TBCs with top coats containing tetragonal phase had the highest durability. Degradation of such TBCs resulted mainly from oxidation of the bond coats. For top coats with a greater amount of monoclinic phase, thermal mismatch stress occurred during cooling and detrimentally affected durability. The morphology of TBCs coatings before and after laser glazing was discussed in Ref. [40].

There are dimensionless variables used to characterize the thermodynamic structure change in materials by laser beam. These variables include normalized temperature "T_P^*", normalized depth l^* of remelting or hardened zone, beam power q^* and the dimensionless beam traverse rate v^*. The equations govern these variables are as follows [41]:

$$T_P^* = \frac{T_P - T_0}{T_m - T_0} \qquad (T_P, T_0, T_m \text{ in K}) \tag{1}$$

where T_0 is the initial temperature of the material. Similarly, the transformation depth l is normalized using the beam radius r_B to give the normalized depth, l^*:

$$l^* = \frac{l}{r_B} \qquad (l \text{ and } r_B \text{ in m}) \tag{2}$$

The dimensionless beam power q^* and the dimensionless beam traverse rate v^*:

$$q* = \frac{Aq}{r_B\lambda(T_m - T_0)} \qquad (q \text{ in J s}^{-1} \text{ and } \lambda \text{ in J s}^{-1}\,\text{m}^{-1}\,\text{K}^{-1}) \tag{3}$$

$$v^* = \frac{vr_B}{a} \qquad (v \text{ in m s}^{-1}) \tag{4}$$

where A is the material absorptivity, q is the incident beam power, r_B is the beam radius, λ is the thermal conductivity, v is the traverse rate, and a is the thermal diffusivity.

A desired thermodynamic structural change in a material can be achieved when the laser beam heats the surface to 60% of the melting temperature. The theoretical limits of the process are defined by the need to heat the surface of the material to the transformation temperature ($T_P^* = 0.6$), but not above the melting temperature ($T_P^* = 1$). In laser processing, the structural changes result from thermal cycles and modifications to composition. Phase transformations occur because of a *thermodynamic* driving force that causes one phase to be more stable than others under a given set of conditions. Under *equilibrium* conditions, the phase transformation proceeds to completion. However, the *rate* of transformation in thermally activated processes is governed by a *kinetic* mechanism, such as diffusion. The equilibrium microstructure may then not have time to form, and a metastable phase forms instead [41].

In this work, the laser beam was employed as heat source for sealing and hardening the surface of YSZ coating. The influence of laser power density, scan rate and working distance on the microstructure of laser treated YSZ coating was investigated. The Vickers hardness test was carried out to investigate the influence of microstructure and grain size on the hardness of TBCs.

Table 1
Spray parameters of YSZ coating.

Powder	ZrO_2 8 wt.% yttria
Anode diameter (mm)	(ϕ 7.5)
Arc current (A)	500
Arc voltage (V)	30
Ar plasma forming flow rate (l/min)	47.4
Ar carrier gas flow rate (l/min)	27
Spray distance (mm)	100
Relative scan velocity (mm/s)	60 (8 passes)
Feedstock mass rate (g/min)	15

2. Experimental procedure

2.1. Materials and thermal spray process

Commercial YSZ powder (8 wt.% Y_2O_3) was supplied by Coaken Techno Co., Ltd. Osaka, Japan and used as feedstock. The average particle size is +25–45 μm and the particle morphology is angular. Plasma spray system-model PG-series (Coaken Techno Co., Ltd. Osaka/Japan) was employed in deposition of YSZ coating onto mild steel substrates (12 cm × 5 cm × 0.3 cm). The substrate was grit blasted with alumina (>200 μm) to roughen the surface and cleaned before applying the coatings. The surface roughness was 20–50 μm. The spray parameters are listed in Table 1. Argon was used as primary working gas and carrier for the feedstock. The arc current was adjusted at 500 A and arc voltage at 30 V. Details about plasma spray gun set up can be found in Ref. [42].

2.2. Laser treatment process

YSZ coatings were laser glazed using a 2.5 kW continuous-wave, fiber-coupled lamp-pumped Nd:YAG laser. Laser treatment was achieved at different laser power densities: 157, 50, 34, and 22.5 MW/m^2. The spot size was changed from 3 to 4.5 mm by changing the working distance from 211 to 221 mm. Two beam scan rates at 2 and 3 m/min were used. The laser process parameters are listed in Table 2. The surface roughness of as-sprayed zirconia is approximately 20–30 μm. Five tracks were achieved on the YSZ coating by changing the laser beam power, scan speed, operating distance and spot size. The laser irradiation angle was normal to the surface.

2.3. Characterization techniques

Morphology of as-sprayed and laser glazed YSZ coating were observed via field emission scanning electron microscope (Zeiss SUPRA 40VP FESEM). Samples of dimensions 20 mm × 10 mm × 3 mm were cut from the as-sprayed coated coupons and mounted in hot-resin; followed by grinding with emery papers, polishing with diamond paste and cleaning with water and ethanol. The glazed samples were cut with dimensions 5 mm × 10 mm × 3 mm and cleaned with ethanol using ultra-sonic device. All observed samples were gold plated via sputtering pro-

Table 2
Laser glazing parameters for YSZ coating.

Tracks	Laser power on the surface (W)	Laser power density (MW/m^2)	Beam scan rate (m/min)	Distance from lens (mm)	Spot size (mm)
1	1100	157	2	211	3
2	353	50	2	211	3
3	353	50	3	211	3
4	353	22.5	2	221	4.5
5	536	34	2	221	4.5