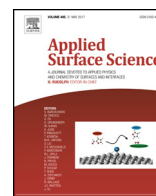




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Laser remelting of plasma-sprayed nanostructured Al_2O_3 –20 wt.% ZrO_2 coatings onto 316L stainless steel

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ABSTRACT

The nanostructured Al_2O_3 –20 wt.% ZrO_2 coatings were fabricated by atmospheric plasma spraying (APS) on the 316L stainless steel and the laser-remelted testing was carried out using a continuous CO_2 laser. The effect of laser treatment on microstructure and mechanical properties of the nanostructured Al_2O_3 –20 wt.% ZrO_2 coatings were also investigated. The results indicate that microstructural inhomogeneity in the coatings such as pores, voids and lamellar structure can be eliminated after laser remelting. When the laser power keeps at a constant, the quantity of surface cavities decrease with the increase of scanning rate whereas the quantity of surface cracks tend to increase. Both cavities and cracks can minimize when the laser power reaches 600 W with the scanning rate of 1000 mm/min. The laser treatment can greatly improve the surface roughness, wear resistance, microhardness, elastic modulus and fracture toughness of the nanostructured Al_2O_3 –20 wt.% ZrO_2 coatings.

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1. Introduction

Surface engineering technology now has been widely used in many industry areas due to its excellent protection properties. Different coatings should be chosen in accordance with the service condition of components materials, such as wear-resistance coatings, corrosion-resistance coatings, oxidation-resistance coatings and so on [1,2]. Thermal barrier coatings, such as Al_2O_3 – ZrO_2 coatings, are playing an important role in the fields of diesel engines, aviation and aerospace engines [3–6], owing to its superior physical and chemical properties. The Al_2O_3 – ZrO_2 coatings fabricated by APS onto the 316L stainless steel can protect the substrate from external damages like abrasion, oxidation, corrosion, which can often happen accompanied with high temperature atmosphere [7–9].

Almost all kinds of materials, including refractory ceramic materials, can be converted to the surface coating by plasma spraying due to its high-temperature characteristic [10]. The particles, which are melted by the plasma torch and sprayed from the plasma gun, will get high velocities, and they cool and solidify rapidly as soon as they impact the substrate at room temperature. However, there are some problems about plasma-sprayed coatings that cannot be

neglected. The primary one is the microstructural inhomogeneity, such as high porosity and lamellar structure [11–13], which reduces the oxidation, wear and corrosion resistance. The second one is the insufficient adhesion strength between the coating and substrate [14], which leads the coating to tend to spallation under some extreme conditions such as heavy load and high frequency thermal shock.

Post-treatment by laser remelting tends to be a promising method to solve the above-mentioned problems [15,16]. The laser treatment can remove the pores and lamellar structure in the coating to achieve homogeneous microstructure and enhance the bond strength by elements diffusion nearby the interface between the coating and substrate [17]. The wear resistance, corrosion resistance and thermal shock resistance of the coatings have been improved by means of laser remelting [18–20]. However, the thermal stress can be induced during the remelting process due to the rapid heating and cooling characteristic of laser treatment, which will inevitably results in some cracks in the coatings [21].

Based on the advantages of laser remelting, a series of laser parameters was designed to remelt the plasma-sprayed nanostructured Al_2O_3 – ZrO_2 coatings onto 316L stainless steel in this paper. The effect of laser remelting on microstructure and mechanical properties of the plasma-sprayed nanostructured Al_2O_3 – ZrO_2 coatings was investigated systematically.

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Table 1
The composition of the substrate (wt.%).

Elements	Fe	Cr	Ni	Mo	Mn	Si	P	S	C
Content	Bal.	17.6	14.2	2.7	1.8	0.9	0.028	0.008	0.025

Table 2
Plasma spray parameters used for depositing Al₂O₃–20 wt.%ZrO₂ coatings.

Plasma spray parameters	Values
Voltage (V)	65
Current (A)	650
Primary gas (Ar) flow rate (SCFH ^a)	100
Secondary gas (H ₂) flow rate (SCFH)	50
Powder feed rate (g/h)	1000–1500
Spray distance (mm)	100
Spray angle (°)	90

^a 1SCFH = 0.472 L/min.**Table 3**
Parameters of laser remelting.

Experimental No.	Laser power (W)	Scanning speed (mm/min)	Beam size (mm)
1	600	1400	2.5
2	600	1000	2.5
3	600	800	2.5
4	500	800	2.5
5	400	800	2.5
6	800	800	2.5

2. Experimental procedure

2.1. Materials and coatings fabrication

The substrate was 316L stainless steel with the dimension of 20 × 20 × 8 mm³, which was machined by wire-electrode cutting. The composition of the substrate is listed in Table 1. The substrate was cleaned in alcohol and then grit-blasted by JZB box-sandblast apparatus (Jinjiuzhuoer, Beijing) before spraying. The feedstock used for plasma spraying was reconstituted agglomerates with the average size of 50 μm derived from Al₂O₃ (50 nm, α-phase, 99.9% purity, Rare Chem. Co., Ltd., China) and 8YSZ (60 nm, tetragonal phase, 99.9% purity, Rare Chem. Co., Ltd., China) nanoparticles. The coatings were deposited onto the substrate by atmospheric plasma spraying (APS) (Sulzer Metco 9MB plasma gun, USA). The thickness of the coatings is about 300 μm. The plasma spraying parameters are shown in Table 2.

2.2. Laser remelting test

The laser treatment was carried out by a continuous wave (wavelength 10.6 μm) CO₂ laser device (DL-HL-T5000, China) with a defocused beam of about 2.5 mm diameter on the surface of as-sprayed coatings. In order to find the most smooth and integrated morphology of the laser treated zones, a wide range of laser experiment parameters have been designed in this work. Considering the high absorption of the laser radiation by ZrO₂, low laser energy can remelt the coatings. The designed laser processing parameters are listed in Table 3.

2.3. Characterization

The microstructure of as-sprayed and laser-remelted coatings was observed by scanning electron microscopy (SEM, Quanta200,

FEI, USA) equipped with energy dispersive spectroscopy (EDS). The phase analysis was carried out before and after laser remelting using an X-ray diffractometer (D/max-γB, Japan; 45 kV, 40 mA, Cu Kα radiation) with a scanning speed of 4°/min.

A Vickers microhardness tester (HV-1000) was used to measure the microhardness of the as-sprayed and laser-remelted coatings. The normal load was 0.3 kgf and the holding time was 15 s. The effect of laser remelting on the elastic modulus and nanohardness was examined by a nanoindenter (Nano-Indenter XP, Agilent, USA). The sliding tribological behavior of coatings before and after laser treatment was performed using a ball-on-disc tester (Zhongkekai-hua Co., Ltd., China) at ambient temperature (20 °C) and 60% relative humidity. The wear scar was characterized by a JB-4C surface roughmeter (Taiming Optical instrument Co., Ltd., Shanghai).

3. Results and discussion

Fig. 1 shows the surface morphologies of laser-treated coatings with different laser parameters and as-sprayed coatings. The surface of laser-treated coatings is smoother and denser than as-sprayed coatings though there are some cracks and voids. When the laser power keeps a constant 600 W, the number of voids decreases as the laser scanning velocity reduces from 1400 to 800 mm/min. However, the quantity of cracks tend to increase (Fig. 1a–c). It is due to the fact that pores in the coatings do not have enough time to escape when the laser scanning speed is relatively higher. Consequently, those pores aggregate to form the small cavities onto the surface (Fig. 1a). The big cavities formation can owe to another explanation. Ceramic coatings where exposed to the laser irradiation are heated rapidly to the melting point then melt. However, due to the high laser scanning velocity and sticky characteristic of the molten ceramic materials, the mixed gas bubble in the fusion process retains on the surface with the quick cooling of the molten coatings after the laser beam passes.

Like the viscous molten ceramic charged with gas tending to erupt explosively, this phenomenon has also been discovered in the laser remelting process as shown in Fig. 2a, the molten viscous ceramic coatings in the weld pool have been blown up spattering to the ‘shore’ under the high vapor pressure caused by laser heating, while Fig. 2b presents the normal boundary of the molten pool.

The laser energy density (laser energy per area unit) is proportional to laser power while is inverse to scanning velocity and beam size [15]. Laser energy density increases as the laser scanning speed declines. When the laser scanning speed drops to some extent, the coatings will become more homogenous and compact, and this results in the relatively high thermal conductivity of the laser-treated coatings. After the laser beam passes, the heat in the molten regions is conducted quickly to the substrate and external environment. The remelted coatings then cool, solidify and contract promptly, thus many cracks happen as a consequence of the restriction of the substrate and side coatings (Fig. 1c). When the scanning speed remains stable, the voids will appear on the surface of the laser-treated coatings. If the laser power is not enough to fully remelt the coatings, the pores will go up to the surface to gather and form the voids (Fig. 1e). On the other hand, The coatings will overburn seriously if the laser power is too large (Fig. 1f). It is important and necessary to explore the proper laser parameters to obtain the relatively better performance of laser-remelted coatings. After the early exploration, we find that when the laser power reaches 600 W and the scanning velocity is 1000 mm/min (No. 2), both voids and cracks reduce to a minimum (Fig. 1b).

The residual thermal stress, which generated during the laser-remelted processing, leads to the cracks in the remelted coatings. Meanwhile, the thermal expansion mismatch between substrate and coating will also result in residual stress during cooling stage.

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