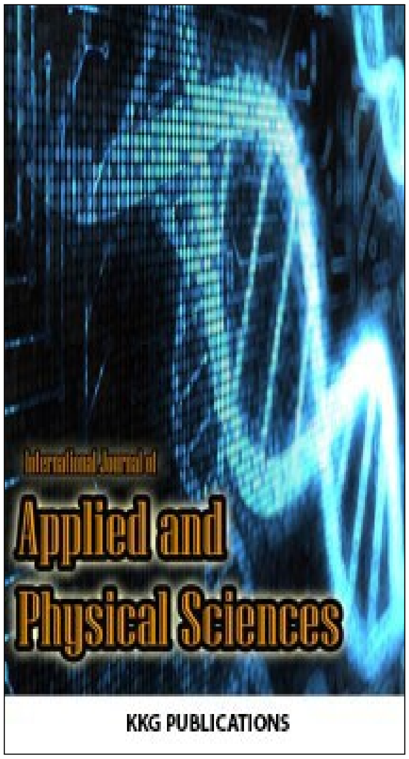

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Laser Surface Texturing of Nickel Superalloy to Improve Adhesion Bond Strength of Thermal Barrier Coating

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LASER SURFACE TEXTURING OF NICKEL SUPERALLOY TO IMPROVE ADHESION BOND STRENGTH OF THERMAL BARRIER COATING

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Abstract. Laser surface texturing was adopted to improve the adhesion bond strength of thermal barrier coating generally used in aero turbine components. A picosecond Q-switched Nd: YAG laser operating at 532 nm wavelength was used to perform laser surface texturing. Two different types of texture, namely, an oriented square pattern was having 250 μm width and 250 μm pitch and a trapezoidal pattern having 150 μm width and 250 μm pitch were textured on nickel superalloy C-263 surface before air plasma spraying of NiCrAlY bond coat. Optical Microscopes (OM) and White Light Interferometer (WLI) characterized the microstructure and surface morphology of these patterns. The pre-defined texture in the laser-ablated region and greater surface contact enhanced the mechanical interlocking with the bond coat. The generation of grooves increased the surface roughness of textured substrate 6 times greater than grit blasting. Further, the trapezoidal pattern exhibited higher surface roughness due to a greater laser ablated area. The adherence was tested by the adhesion bond strength test, which showed 35 MPa and 37 MPa adhesive strength for oriented square and trapezoidal patterns. The fractal analysis showed that the textured substrate failed predominantly by cohesion.

INTRODUCTION

The hot gas path components of advanced gas turbine engines are typically made of high temperature strength and corrosion resistant Nickel based superalloy materials. However, the need for higher power and efficiency of gas turbines resulted in the raise of combustion temperature utmost nearer to the superalloy melting temperature. Hence, Thermal Barrier Coatings (TBC) are applied over the superalloy base material to withstand higher turbine inlet temperature. This TBC aids in reducing the underlying substrate temperature upto 300 °C. As a result, operating temperature is increased above 1400 °C thereby improving turbine efficiency [1], [2]. TBC generally comprised of 2 layers: metallic Bond Coat (BC) and a ceramic Top Coat (TC). It employs 6-8 wt.% YSZ for TC whereas the BC is based on Ni(Co)-Cr-Al-Y alloy. The TC provides thermal insulation while the BC protects the substrate surface from chemical attack. The adherence between the substrate and TBC is a critical property which governs the nature of bonding [3]. Hence, the substrate surface pretreatment becomes mandatory to alter the mechanical and physicochemical behavior of substrate surface in enhancing its adhesion with TBC. Conventionally, the surfaces are roughened to promote adhesion by mechanical degreasing and grit blasting. Vapor degreasers are used to remove lubricants, body oil, grease, rust or other corrosion products from the substrate surface. This results in chemical modification of the treated surface thereby promoting adhesion. In recent times, alkaline cleaners and aqueous detergents are also employed due to its non-hazardous nature. Moreover, all these degreasers must be properly handled and used in well ventilated areas. On the contrary, grit blasting employs abrasive grits such as aluminium oxide, chilled iron, sand, crushed steel or silicon carbide for surface preparation before thermal spraying. The impingement of abrasive grits with optimized air pressure modifies the surface morphology by imparting random roughness. This generated roughness promotes mechanical anchorage of spray coating to the substrate. However, this process is limited due to the entrapment of grit particles, surface embrittlement, generation of compressive stress and potential cracks over the surface [4], [5], [6]. Hence, new technologies employing laser is on the verge of development to improve the surface properties thereby achieving high quality coating. Laser surface treatment proved advantageous over other conventional technique due to its eco-compatibility, repeatability, ease of manufacturing and greater flexibility.

Laser Surface Texturing (LST) is a novel surface pretreatment technique which improves the mechanical property by generating micro or nano-textures [7]. It is predominantly employed to improve tribo logical performance of mechanical component. The created surface texture is able to reduce

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friction, wear and contact temperature and also increase hydrodynamic load carrying capacity and fluid film stiffness [8], [9]. Recently, LST has gained attention as a pretreatment technique to enhance surface adhesion between substrate and coating. Hence, immense research on identification and optimization of different surface topographies are needed to replace the existing grit blasting technique in enhancing the adhesion of TBC.

LITERATURE REVIEW

Laser ablation was performed on almost all type of materials such as polymers, ceramics and metals for modification of surface topology [10] by generating microcolumnar arrays [11] and grooves [12] on the substrate surface. It was reported that the bond strength enhancement was mainly due to greater surface area, better mechanical interlocking and surface chemistry modification between adherend and adhesive [10], [11], [12]. In recent times, predefined pattern were created on the substrate surface by LST to enhance coating adhesion. [13] textured dimple pattern on aluminium alloy and coated with Ni-Al powder. The patterning strategy comprised of generating a series of equidistant lines of holes on the substrate surface. Tensile adhesion test results showed that the drilled hole angle had no impact on adhesion strength whereas the adhesion strength increased with reduction in pitch distance. The patterned surface was characterized by mixed mode of failure [14]. [15] investigated adhesive bonding behavior of Ti6Al4V alloy by performing LST. The dimple pattern was obtained by point by point percussion drilling operation whereas grid and chaotic pattern employed surface scanning strategy. The molten material generation had a greater effect on adhesion property. The generation of air entrapment and increased capillary pressure resulted in incomplete filling of micro-holes in dimpled structure by adhesive. The laser parameters such as pattern geometry, frequency and power were controlled and optimized to achieve high quality texture which in turn influenced the coating adhesion [16], [17].

The quantitative testing of coating substrate system was essential to evaluate the in-service life span of a component. Moreover, nature and interfacial strength of bond forces such as ionic, covalent, metallic and Van der Walls forces were governed by adhesion [18]. The adhesive strength was determined by performing pull off adhesion test, Laser Adhesion Test (LASAT) and shear test [15, 19]. The test result showed that full cohesive failure was encountered in grid pattern whereas partial cohesive failure in dimple pattern [13], [14], [20]. A portion of the textured substrate failed in the case of chaotic pattern. On the contrary, grit blasted specimen failed adhesively [15]. It was studied that higher surface roughness obtained on the substrate surface by texturing contributed to better mechanical interlocking effect compared to grit blasting. Hence, higher energy was required for interfacial breaking in the case of textured specimen due to its mixed mode behavior. Also, the generated pattern served as a barrier for crack propagation. The bond strength for patterned surface was found to be ~ 35% higher than grit blasted specimen [14], [15], [20]. It is evident from these studies that there is a greater need to conceptualize and explore different pattern geometry and to identify the optimal surface pattern. Hence, the evolution of the effect of the textured surfaces on the adhesion performance and the type of failure that occurs after plasma spray coating needs to be investigated greatly.

In this paper, oriented square and trapezoidal pattern were laser surface textured over C-263 substrate surface which was followed by air plasma spraying of bond coat. The microstructure, adhesive strength and fracture behavior of the textured specimen were compared with the grit blasted specimen.

EXPERIMENTATION

Material Preparation

Nickel alloy C-263 (nickel-cobalt-chromium-molybdenum alloy) substrate was machined into cylindrical form having 25 mm diameter and 80 mm length. The chemical composition of C-263 alloy is listed in Table 1. The substrate top surface was polished using coarser to finer grit size sand papers. Cloth polishing was performed by adding alumina of 3 microns size.

TABLE 1
CHEMICAL COMPOSITION OF C-263 ALLOY

Ni	Cr	Co	Mo	Si	Ti	Mn	Al	Cu	C	Fe
Bal	21.7	19.2	5.85	0.07	1.8	0.56	0.47	0.18	0.06	0.03

Laser Surface Texturing

LST was conducted with a picosecond Q-switched Nd: YAG laser operated at 532 nm wavelength, 650 ps pulse duration, 65 μJ pulse energy and maximum average output power of 3 W having 45 kHz pulse frequency. Gaussian energy distribution was exhibited by the circular laser beam having 90 m beam diameter. Also, the beam was raster scanned using computer controlled galvo scanner. The scanning speed was kept constant at 10 mm/sec. Linear scan was performed to obtain the predetermined texture. The laser head coupled to a CNC galvo controller was advanced progressively along the Z-axis in between each set of passes to attain the required crater depth. The laser was scanned with 20% overlapping ratio as the beam profile followed a Gaussian distribution. Oriented square pattern having 250 m width and 250 μm pitch and trapezoidal pattern having 150 μm width and 250 m pitch were textured on the C-263 alloy substrate surface. The pitch of the texture was chosen to be greater than the average grain size of sprayed powder. The experimental setup used to perform LST is represented schematically in Figure 1.

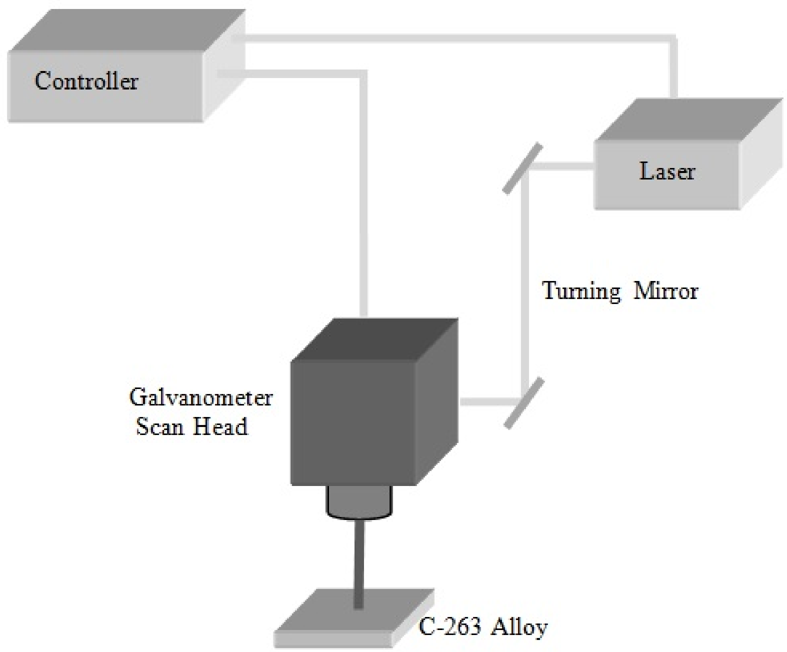

Fig. 1 . Schematic diagram of experimental setup for laser surface texturing

Microstructural Characterization

The microstructure of the textured specimen was characterized using OM (Olympus, Japan). The surface roughness of textured samples was measured using WLI (Rtec Instruments, USA).

Air Plasma Spraying

Commercially available NiCrAlY (Ni22Cr10Al1.0Y wt.%, AMDRY 962) powder having 50 μm-100 μm average grain size was deposited as a bond coat for a thickness of 400 m over the patterned surface. This was performed by plasma spraying with optimized parameters.

Adhesion Bond Strength Test

Adhesion bond strength test as per ASTM C 633 Standard [21] was performed to evaluate the adhesive strength of plasma sprayed coating as shown in Figure 2. The coated substrate was glued using 3M Scotch-Weld Epoxy Adhesive with mating part having same dimension. It was allowed to cure for 80 min at 150 °C. Cross head speed of 0.05 mm/min was applied for all samples and the bond strength was calculated using equation (1).

$$\text{Bond strength} = \frac{\text{(Load at failure)}}{\text{(Failed face area)}} \quad (1)$$

$$\text{Failure area} = (\pi d^2)/4 \quad (2)$$

Where d is the diameter of the failed face.

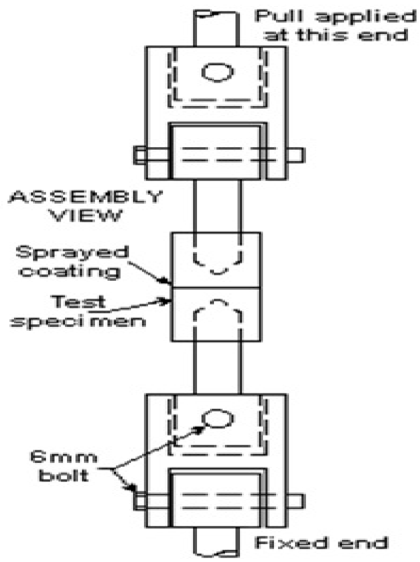

Fig. 2 . Set-up of adhesion strength test

RESULTS AND DISCUSSION

Morphological Analysis of Laser Textured Surface

The OM and WLI images of grit blasted, oriented square and trapezoidal patterned surfaces are shown in Figure 3 and 4, respectively. The depth of the oriented square pattern and trapezoidal pattern was kept constant at 100 m by varying the number of passes. The cross section of single track exhibited a V-geometry because of higher energy density delivered at the beam center. The geometry was changed to U-profile with beam overlapping and the number of laser pass was determined from the required pitch.

The surface roughness measure was obtained through WLI. The average maximum height of the roughness, R_z was evaluated which provided a primary quantitative distinction among the treated surfaces. The R_z value was found to be 15 μm for grit blasted specimen. On the other hand, the oriented square and trapezoidal pattern exhibited R_z of 92 μm and 116 μm, respectively which showed ~ 6 times increase in roughness compared to grit blasting. A significant increase in roughness of trapezoidal pattern was due to the greater groove density.

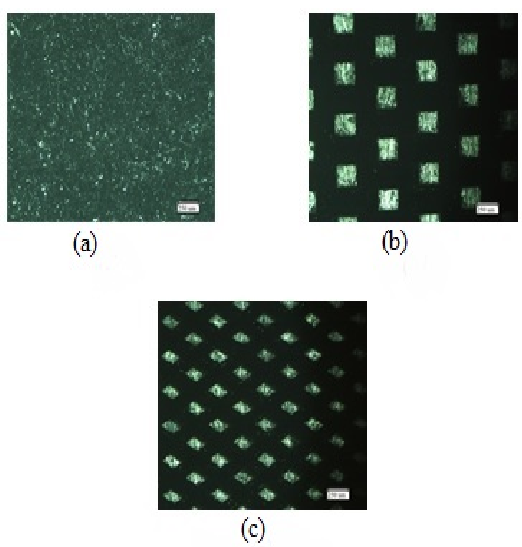

Fig. 3 . Optical Microscopy observation of (a) grit blasted, (b) oriented square, and (c) trapezoidal pattern

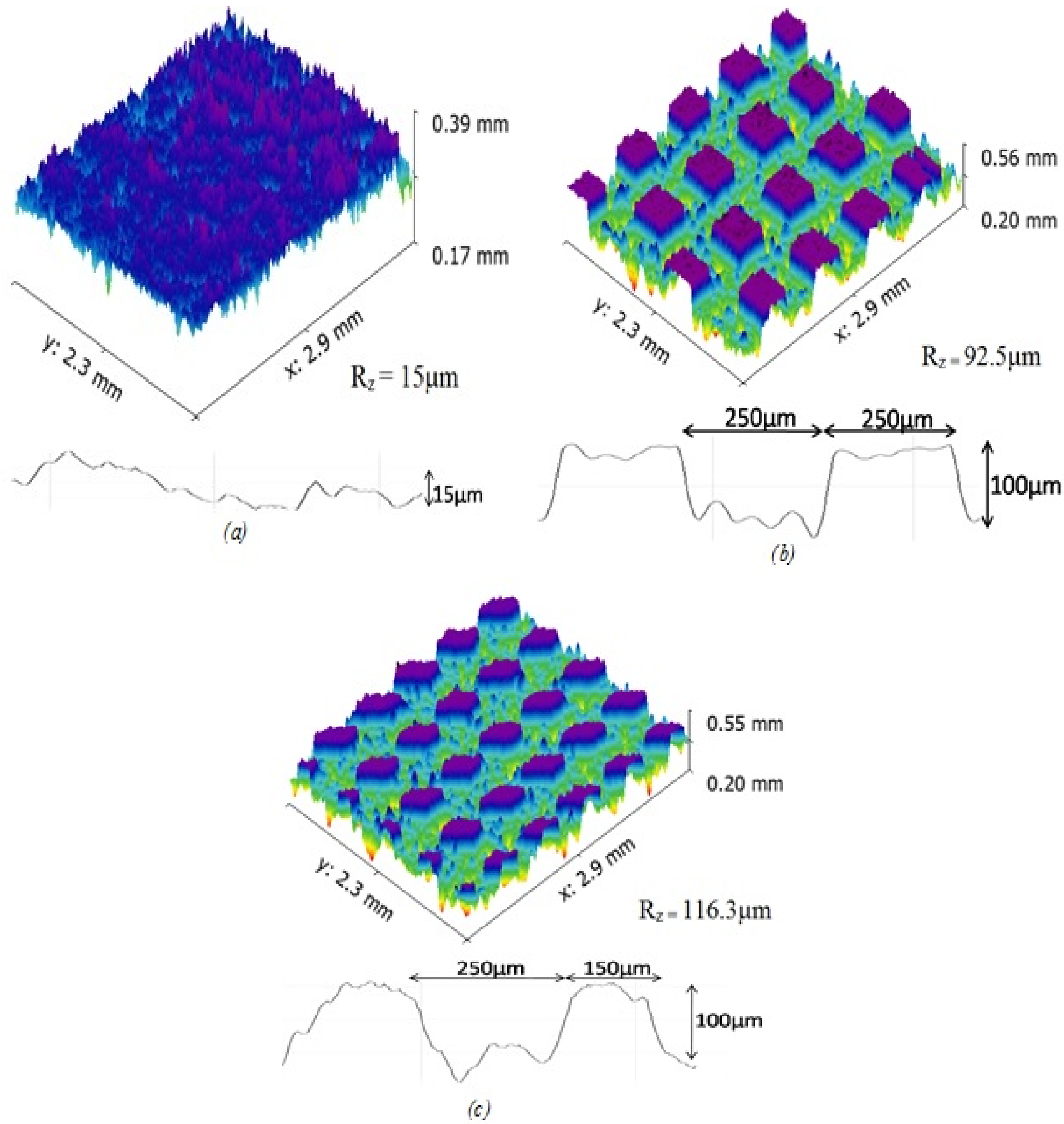

Fig. 4 . WLI images and 2D topography of (a) grit blasted (b) oriented square, and (c) trapezoidal pattern surfaces

Bond Strength Analysis

The tensile force applied for each test specimen is shown in Figure 5. The oriented square and trapezoidal pattern exhibited bond strength of 35 MPa and 37 MPa, respectively which was higher than the grit blasted specimen bond strength of 26 MPa. It can be seen that higher surface roughness and greater surface area contributed to better adhesion in patterned specimen. The adhesion strength of all test specimens is listed in Table 2.

TABLE 2
ADHESION STRENGTH FOR DIFFERENT SURFACES

Surface Treatment	Maximum Force (kN)	Adhesion Strength (MPa)
Grit Blasting	12.80	26
Oriented Square Pattern	17.18	35
Trapezoidal Pattern	17.92	37

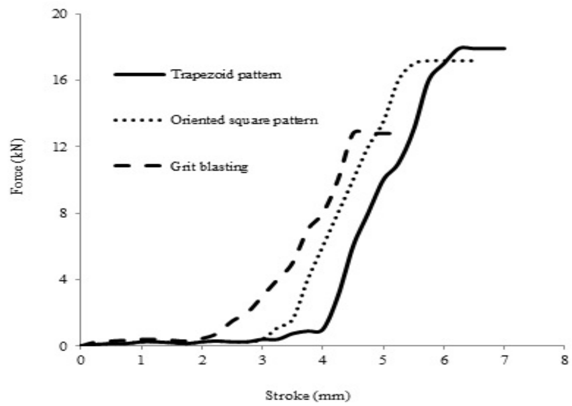

Fig. 5 . Normal force vs stroke of adhesion bond test for test specimens

Theoretically, the adhesion ratio which represents the substrate/coating contact was determined using equation (3).

$$R = \frac{(\text{Adhesion area})}{(\text{Plane area})} \tag{3}$$

The adhesion area for one square pillar and one trapezoidal pillar were calculated. The equivalent planar surface area was also determined neglecting the surface roughness. Table 3 lists the adhesion ratio for both patterns. Single square pillar showed an adhesion ratio of 2.6 compared to its equivalent flat surface. Similarly, trapezoidal pillar exhibited adhesion ratio of 3.5. It was observed that the trapezoidal pattern exhibited higher contact compared with square pattern. This increase in ratio attribute to improved mechanical interlocking between the bond coat and the textured substrate and improved the adhesion strength [22].

TABLE 3
ADHESION STRENGTH FOR DIFFERENT SURFACES

Pattern	Adhesion Area (μm^2)	Plane area (μm^2)	*R*
Oriented Square Pattern	162500	62500	2.6
Trapezoidal Pattern	84500	24000	3.5

Failure Analysis

The fractured surface of grit blasted, oriented square and trapezoidal patterned substrate is shown in Figure 6.

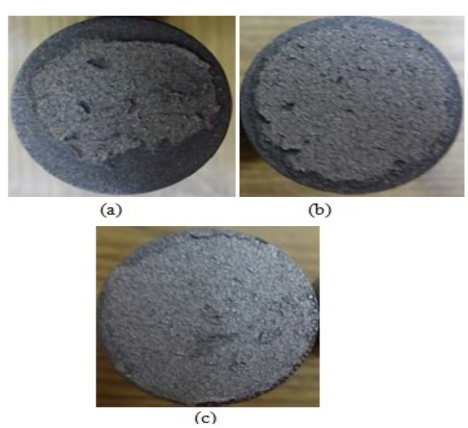

Fig. 6 . Fractured surface of (a) grit blasted, (b) oriented square and, (c) trapezoidal patterned specimen

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It was found that adhesive failure was predominant in the fractured surface of grit blasted specimen. On the other hand, the laser textured surfaces failed cohesively i.e., within the coating. This showed that the laser treated surfaces contributed to improved mechanical interlocking effect in comparison with grit blasted specimen.

CONCLUSION

The effect of laser surface texturing on the Nickel alloy surface to enhance coating adhesion strength was investigated. Based on the results, the following conclusions were drawn.

- The pitch and width of the textured pattern needs strategic selection for optimum groove density to enhance the bond strength.
- The topography of the textures needs to be designed for higher adhesion area or lower plane area for improved adhesion ratio.
- Predefined textured patterns could alter the mode of failure vital for improved bond strength.

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— This article does not have any appendix. —