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# Online monitoring of laser remelting of plasma sprayed coatings to study the effect of cooling rate on residual stress and mechanical properties

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ABSTRACT

This investigation deals with laser remelting of plasma sprayed alumina and chromia coatings. The time-temperature history of the laser remelted zone was recorded using an infrared pyrometer during the remelting operation. Cooling rates, under varying scanning speed, were determined from the time temperature curve. Surface morphology, microstructure, and phases of the laser treated and as-sprayed coatings were characterized using scanning electron microscopy, optical microscopy, X-ray diffraction, respectively. X-ray diffraction was also employed to measure the surface residual stress of the coatings. Inherent features of plasma sprayed coatings like porosity and inter-lamellar boundary were obliterated upon laser remelting. A columnar grain growth perpendicular to the laser scanning direction was observed. The range of roughness of the as-sprayed coatings reduced from 6 to 8 μm to 1–2 μm in the remelted layers. For both coatings, more than 90% reduction in porosity was found upon laser remelting. Surface residual stress of the as-sprayed alumina and chromia coatings was found to be tensile and compressive, respectively. Within the limits of the testing condition the tensile residual stress of the remelted layers increased by up to around 500% in the alumina coatings. In the chromia coating a decrease of compressive stress by up to around 80% was recorded. In the remelted layer the tensile nature of the stress showed a tendency to increase with an increase in the cooling rate. However, the state of stress of the as-sprayed layer, i.e., tensile or compressive, was retained in the remelted layer. The residual stress was found to decrease in the remelted layer with an increase in the degree of overlap of the remelted tracks.

## 1. Introduction

Surface engineering embraces a wide range of technologies utilized to modify the surface properties of metallic and non-metallic components for engineering applications [1,2]. Thermal spraying is a well-known surface modification technique that is utilized to deposit thick coatings on the substrate surface. Plasma spraying is the most versatile of all the thermal spraying processes. It is used to deposit metals, ceramic and polymer coatings [3]. This process is particularly suitable for materials with a high melting point, such as ceramics.

The purpose of ceramic coating is to endow the surface of the coated component with improved properties, e.g., wear resistance [4]. Alumina, chromia, alumina-titania, zirconia, titania are the examples of some of the ceramic coating materials [5]. Alumina coating is particularly suitable for wear resistance applications owing to its high hardness and chemical stability [6,7]. Plasma sprayed alumina coating is used in automotive and electronic industry. On the other hand, chromia coating is widely accepted for corrosion resistant application. This coating is used in printing rolls, piston rings of IC engines and pumps [8,9].

Plasma sprayed coatings inherently possess some structural defects, e.g., porosity, micro-cracks, etc. [10]. It is possible to modify the structural aspects of the plasma sprayed coatings using flame, arc, plasma and laser. Amongst these heat sources, the laser is considered superior for its precise control of energy input without affecting the properties of other parts of the coating [11]. Laser remelting also provides a high cooling rate that cannot be achieved by other post processing techniques. The high solidification rate of this process leads to a fine dendritic microstructure with uniform redistribution of grains [12]. These coatings exhibit higher coating hardness, wear resistance, and thermal shock resistance as compared to the as-sprayed coatings [13].

Sivakumar and Mordike (1988) utilized a $CO_2$ laser to remelt plasma sprayed alumina, zirconia and titania coatings [14]. The remelted layer was found to be almost pore free. However, both longitudinal and transverse cracks were found to develop in the remelted layer. In general, longitudinal cracks that run parallel to the coating are detrimental since they may cause coating spallation. Transverse cracking, on the other hand, can help to accommodate the strain

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evolved during thermal cycling and thus, can be beneficial for the coating in some applications. An improvement in wear resistance of plasma sprayed ceramic coatings upon laser remelting has been demonstrated by several authors [15,16].

Krishnan et al. [17] found that laser remelting transforms the metastable γ-$Al_2O_3$ phase into stable α-$Al_2O_3$. The restoration of thermodynamically stable α-$Al_2O_3$ has been ascribed to the thermally induced relaxation of defect spinel structured γ-$Al_2O_3$ phase. During plasma spraying, the rhombohedral α-$Al_2O_3$ present in the powder was converted to metastable γ-$Al_2O_3$ phase. This is attributed to a lower nucleation barrier of the γ-$Al_2O_3$ phase as compared to the other alumina polymorphs like α-$Al_2O_3$.

The objective of the work is to monitor the laser remelting process of plasma sprayed alumina and chromia coating at different parametric conditions and to find out the effect of varying cooling rates on the residual stress and mechanical properties of the remelted coating. In general, not too many reports are available on the laser remelting of thermally sprayed ceramic oxide coatings. So far the author found only one report on the remelting of plasma sprayed chromia coating [18]. The cooling rate of the remelting process is expected to affect the mechanical properties of the remelted coatings. However, to the knowledge of the authors, no report on the effect of this cooling rate is available in the literature. The present work in that way is a novel attempt to investigate the mechanical properties, and surface residual stress of plasma sprayed ceramic coating with and without laser remelting.

## 2. Experimental procedure

### 2.1. Materials

Commercially available alumina ($Al_2O_3$) and chromia ($Cr_2O_3$) powders (Oerlikon Metco, Switzerland) were sprayed onto C-20 steel substrate of dimension 50 mm × 75 mm × 5 mm (thickness). Alumina and chromia powders of size ranges −45+15 μm and −125+11 μm, respectively, were utilized as top coats. A bond coat of Ni-5 wt% Al was provided between the ceramic top coat and the substrate.

### 2.2. Plasma spraying procedure

C-20 steel coupons were grit blasted inside a grit blasting cabinet (Sandstorm, Bangalore, India) using alumina grits of mesh size 24 at 100 psi (0.7 MPa) blasting pressure at a standoff distance of 125 mm. The roughness (Ra) of the grit blasted surface was found to be 6.5 ± 0.4 μm. The grit blasted samples were ultrasonically cleaned for 15 min in 2-propanol solution. Immediately after cleaning, bond and top coats were plasma sprayed on the substrates using a 9 MB plasmatron (Oerlikon Metco, Switzerland). The plasma spraying parameters used are listed in Table 1.

### 2.3. Laser remelting procedure

Plasma sprayed coatings were remelted using a 2 kW Yb-fiber laser (IPG photonics, Model no. YLR 2000) operating at a wavelength of 1.07 μm. This fiber laser can be operated in continuous mode as well as in pulsed mode. The laser system is attached to a 5-axis CNC machine. A combination of different laser power and scanning speed were used to achieve different energy densities for remelting purpose. The direction of the laser beam was perpendicular to the coating surface, and the beam diameter on the coating surface was set at 5 mm in every case. The parameter ranges used to remelt both types of coatings are listed in Table 2.

**Table 2**
Laser remelting parameters.

| Coating type | Laser power (W) | Scanning speed range (mm/min) | Laser beam diameter (mm) | Shielding gas |
|---|---|---|---|---|
| Alumina | 400–800 | 200–2500 | 5 | Argon |
| Chromia | 300–600 | 200–500 | 5 | Argon |

A single spot monochromatic pyrometer (Micro Epsilon, model: CTLM-2HCF3-C3H, U.S.A.) was utilized to monitor the time-temperature history of the laser remelting process. The pyrometer has the following operational features: operating wavelength 1.6 μm, vision zone 700 μm, acquisition time 1 ms, working temperature range 385–1600 °C. It was also equipped with a pair of guide laser beams to focus at the required point. The pyrometer was kept fixed during online monitoring of the remelting process. To eliminate the effect of reflected laser radiation, a notch filter of 1064 nm ± 25 nm spectral range with an optical density of 3 was used to block the 1070 nm laser radiation [19]. However, the notch filter also blocked a part of the 1.6 μm radiation. Hence, the pyrometer was calibrated with and without the notch filter at the melting temperature of different metals, e.g. steel, copper and aluminium. With the notch filter, the temperature measurement range of the pyrometer is 785–3260 °C.

### 2.4. Characterization of the samples

For microstructural study, samples of 10 × 10 × 5 mm dimensions were sliced from the as-sprayed sample using a low-speed diamond saw (150 low-speed diamond cutter, MTI Corp.). The samples were mounted in resin and polished in their cross sections in a semi-automatic polisher using SiC papers and diamond pastes. Laser treated tracks were sliced, mounted and polished using same procedure noted above. The polished cross sections were observed under a scanning electron microscope (SEM) (EVO 15, Zeiss, Jena, Germany). Phase and surface residual stress investigations were undertaken using a high resolution X-ray diffractometer (Empyrean Cu LFF HR (9430 033 7310 ×) DK411025, Netherlands) generating Cu Kα radiation. The instrument operating voltage and current were 45 kV and 40 mA, respectively. For the measurement of residual stress, the $\sin^2\Psi$ method was implemented using the following nine stage tilt (χ) angles: 0°, ± 22.79°, ± 33.21°, ± 42.13°, ± 50.77°. The residual stress was measured perpendicular to the laser scanning direction. Stage rotation (angle ϕ) was kept unchanged for uniaxial stress measurement. Point source and parallel beam setting were utilized for stress measurement. On the incidence side of the diffractometer, X-Ray lens was used along with an X-Ray mask of 4 mm in series with a divergence slit of 7 mm for the as-sprayed coatings. For the laser remelted tracks X-Ray mask of 2 mm with a divergence slit of 4 mm was used. A Ni filter of 0.020 mm thickness was fitted in the incident beam optics assembly. The scan was performed with step size 0.1° for each coating. The total time taken for stress measurement was 3 h 21 min for each coating. A PIXcel1D-Medipix3 point detector was used in 0D mode to monitor the intensity

**Table 1**
Plasma spraying parameters.

| Sl. no. | Powder | Nozzle diameter (mm) | Stand- off- distance (mm) | Current (A) | Voltage (V) | $N_2$ flow-rate (scfh) | $H_2$ flow-rate (scfh) | Spray rate (gm/min) |
|---|---|---|---|---|---|---|---|---|
| 1. | $Al_2O_3$ | 5 | 125 | 500 | 75 | 50 | 5 | ~ 25 |
| 2. | $Cr_2O_3$ | 5 | 125 | 500 | 75 | 50 | 5 | ~ 45 |
| 3. | Ni-Al | 5 | 125 | 450 | 67 | 50 | Nil | ~ 43 |