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Laser Shock Processing of Al-SiC Composite Coatings*

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Laser shock processing (LSP) is a technique of surface treatment (similar to shot peening) in which laser-induced mechanical shocks develop compressive stresses in the material. The stresses are of sufficient intensity to modify microstructure and properties of the coatings. In the present study, laser shocks of power density of 5 to 8 GW/cm^2 power density, generated by means of a neodymium-glass laser, were used to treat Al + SiC composite coatings deposited by means of a HVOF spraying technique. The laser processed samples were metallographically prepared, and their microstructure was investigated by optical microscope and SEM. The latter was also used to investigate the surface morphology of the laser treated specimens. Finally, the microhardness and oscillating wear resistance of the coatings were tested and compared to data obtained for as-sprayed samples.

Keywords composite coatings, laser shock treatment, metal matrix composites, postprocessing

1. Introduction

Laser shock processing (LSP) is a relatively new postspray technique, where sprayed coatings are laser treated in a mechanical way, in contrast to a frequently used thermal way method (Ref 1). This technique is particularly well adapted to modify carbide coatings, which decompose under high temperature treatments. Laser shock processing was developed in the 1960s and 1970s (Ref 2) and takes advantage of the shock waves created by an expansion of plasma. The plasma results from an interaction of an intense laser pulse, having a power density from 1 to 10 GW/cm^2 and a duration from 1 to 30 ns (Ref 3), with the material.

Two methods of treatment with LSP are possible: (a) direct ablation in which plasma is in direct contact with the coating, and (b) confined treatment (Fig. 1) in which plasma contacts with a double layer system. The latter method has the advantage of preventing the coating from contact with a hot plasma (Ref 4) and increases (3 to 5 times) the pressure of the shock waves (Ref 5).

In the confined treatment process, the laser beam crosses a transparent water overlay and is absorbed in a metallic target, usually of aluminum foil. The foil is partly vaporized and creates the expanding plasma. An incoming water flow confines this expansion in a direction opposite to the coating (Ref 6). The pressures of laser shocks in the treated substrates measured with piezoelectric gauges are from 3 GPa (Ref 2) to 10 GPa (Ref 5). The independent measurements with an interferometric method were made recently (Ref 7). These measurements confirmed previous data, and the pressure values were from 5 to 6 GPa for pulses of power density 8 to 10 GW/cm^2 and of 10 to 30 ns duration. An increase of laser power density above 10 GW/cm^2 results in the dielectric breakdown in water rather than in further increase of the shock pressure.

Use of LSP was reported to improve the fatigue resistance of aluminum alloy (Ref 8), to harden titanium (Ref 4), and to improve the pitting corrosion resistance of martensitic steel (Ref 9). In the present study, the application of LSP to improve the wear resistance of high-velocity oxygen fuel (HVOF) sprayed Al + SiC particulate composite coatings is investigated.

2. Experimental Procedures

The substrates were of an aluminum alloy (Al + 5 wt% Cu + 1 wt% Pb + 1 wt% Mg + 1 wt% Mn + 0.5 wt% Fe) having di-

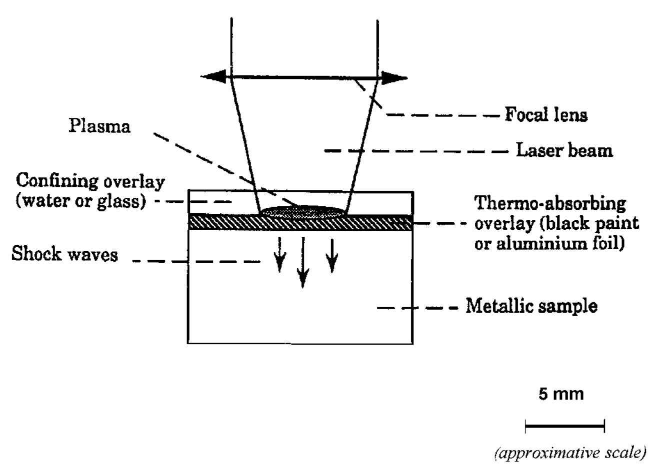

Fig. 1 Sketch of confined treatment with laser shocks

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mensions of 45 mm diameter and 10 mm thick. Prior to coating, the samples were blasted with corundum of grit size from 600 to 850 µm, using a 5 bar pressure. The composite powders were prepared by mechanical blending of aluminum and silicon carbide powders (Table 1).

The powders were sprayed using a Sulzer Metco (Wohlen, Switzerland) HVOF installation with a Diamond Jet torch. The torch was handled manually. In total, 30 substrates were coated. The following operational parameters were used: (a) oxygen pressure of 1.0 MPa at a flow rate of 48 units, (b) propane pressure of 1.6 MPa at a flow rate of 28 units, and (c) air pressure of 0.5 MPa at a flow rate of 52 units. The spray distance and makeup of the feedstock were altered. The coatings exhibited different thicknesses (Table 2).

The LSP experiments were carried out using a neodymium-glass laser with a maximum energy of 40 J and pulse durations ranging from 8 to 10 ns. The laser produced a pulse each 90 s (repetition rate of 0.011 Hz). The beam spot on the coating surface had a diameter of 6 mm. These three parameters can be combined as follows: laser power density = energy/(pulse duration × beam spot area). Initially, the laser power density was 5 GW/cm^2 (sample No. 8 and No. 30), and it increased to 8 GW/cm^2 (sample No. 20). Laser shocks struck each spot one or two times on the surface. Finally, the samples with an even identification code (see Table 2) were treated with a laser power density of 5 GW/cm^2 (pulse duration 10 ns), and a singular shock was applied in one spot. The coatings were protected with a 100 µm thick aluminum adhesive. Water was used as a confining medium (see Fig. 1). The chosen zone was then treated with 36 shocks in total (6 impacts in the *x* direction and 6 impacts in the *y* direction). The geometry of the treated zone is shown (Fig. 2).

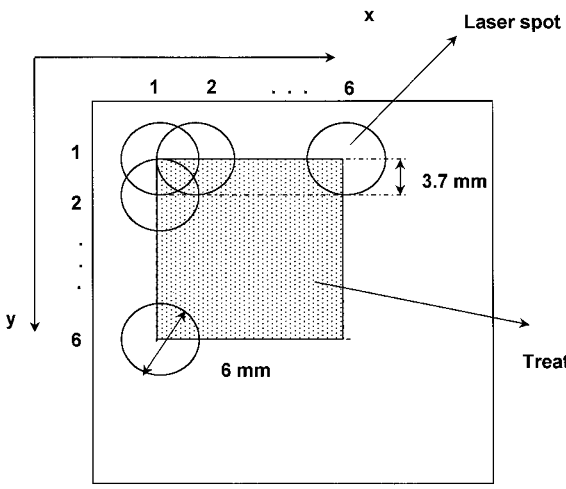

Fig. 2 Geometry of treatment with laser shocks

Finally, the coating in the treated zone was submitted to 4 laser shocks during the treatment. The samples with the odd identification codes were kept in the as-sprayed condition to allow the comparison. The treated samples were submitted to microscopic investigation using a scanning electron microscope (SEM) type JSM 840 (JEOL, Japan) and an optical microscope made by Neophot (Germany). The metallographical sections were made using a setup from Struers (Denmark). The D500 diffractometer from Siemens (Germany) was used to determine the residual stresses using the $\sin^2\psi$ method (see e.g. Ref 10). The roughness of the samples was determined with a type T4000 instrument from Hommelwerke (Germany). The roughness of each sample was determined over a distance of 7 mm. The oscillating wear was characterized by employing an arrangement shown elsewhere (Ref 11) in which a hardened steel (type 100 Cr6) sphere of radius R = 4 mm oscillated with a frequency of 20 Hz under a load of 5 N. The sphere ran a distance of 48 m. Then, the width of the wear track, d_s, was determined. The wear resistance was characterized with the parameter w_L (Ref 11):

$$w_L = d_s^2/(8R)$$

3. Results

The laser shock treatment rendered the surface of the coatings slightly more homogeneous and smooth (Fig. 3). The large individual grains visible on the as-sprayed surface seem to be levelled down on the laser shock treated sample.

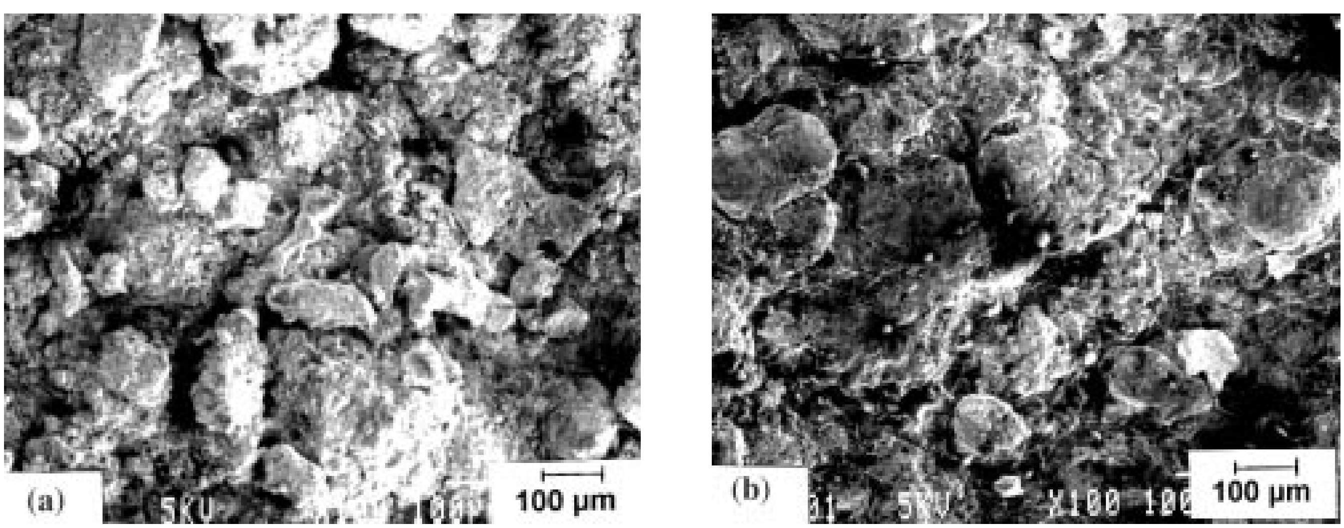

Fig. 3 Scanning electron microscopy (SEM) of the surface of the sample high-velocity oxygen fuel (HVOF) deposited from a spray distance of 200 mm with the powder No. 1 (powder composition Al + 15SiC, reinforcement size 30 µm) (a) after spraying and (b) after laser shock treatment

The HVOF-sprayed composite coatings contained some porosity. The pores appeared between lamellae and in contact between the aluminum matrix and the SiC reinforcement (Fig. 4a). The grains inside the lamellae were equiaxed. The laser shock considerably reduced the porosity and improved the contact between the lamellae, the matrix, and the reinforcement (Fig. 4b).

Moreover, the grains inside lamellae became smaller and more uniaxial than those in the as-sprayed coatings. The grain axes were not, as expected, parallel to the coating surface. This arose due to diffraction of the laser-generated compressive stress waves on structural features having different acoustical impedances (i.e., pores, SiC reinforcement, and the coating/substrate interface). The final waves could, therefore, propagate and modify the microstructure in many directions. The spray distance did not significantly influence the coating microstructures. The coating microstructures depended mainly on the size of SiC grains and the chemical composition of the coatings.

Three pairs of samples were sprayed using different powders (No. 1, 2, and 5) and the same spray distance of 200 mm, with and without laser shock treatment (samples No. 3 and 4, 9 and 10, and 27 and 28) were examined by x-ray to investigate the residual stresses. The determinations were made for the Al (311) peak with the use of 13 different values of the angle ψ (the angle between a normal to the coating surface and a normal to a crystal plane *hkl*). The investigation showed that the peaks had not shifted. This result revealed that the coatings were not under stress in the examined areas that corresponded, for the aluminum matrix, to about 10 to 30 μm in depth. The investigated peaks became considerably broadened after laser treatment (Fig. 5) and indicated that the grains became smaller due to the generation of defects in the crystalline structure from the laser shock. This was also confirmed by the optical microscope observation of etched cross sections (Fig. 4b).

The investigations of microhardness were made on coating cross sections about 70 μm above the interface. Each given

Table 1 Al + SiC composite powders

Powder No.	Composition, wt %	Al powder size, μm	Hard particle	SiC powder size, μm	SiC powder producer
1	Al + 15 SiC	–63 + 45	Pure SiC	–30.7 + 27.7	Elektroschmelzwerk, Kempten, Germany
2	Al + 50 SiC	–63 + 45	Pure SiC	–30.7 + 27.7	Elektroschmelzwerk, Kempten, Germany
3	Al + 15 SiC	–63 + 45	Pure SiC	–3.5 + 2.5	Elektroschmelzwerk, Kempten, Germany
4	Al + 50 SiC	–63 + 45	SiC coated with Ni film	–45 + 30	Institut für Nichteisenmetalle, Freiberg, Germany
5	Al + 50 SiC	–63 + 45	Pure SiC	–3.5 + 2.5	Elektroschmelzwerk, Kempten, Germany

All aluminum samples were obtained from CK Bitterfeld (Germany)

Table 2 Sample code/thickness vs. high-velocity oxygen fuel spray standoff and composite powder type

Spray distance, mm	Sample code/thickness for powder number indicated, μm				
	No. 1	No. 2	No. 3	No. 4	No. 5
150	1/320	11/400	13/320	23/330	25/140
	2/270	12/400	14/300	24/270	26/140
200	3/290	9/340	15/300	21/410	27/130
	4/290	10/330	16/310	22/380	28/110
250	5/300	7/300	17/240	19/380	29/100
	6/230	8/310	18/220	20/390	30/100

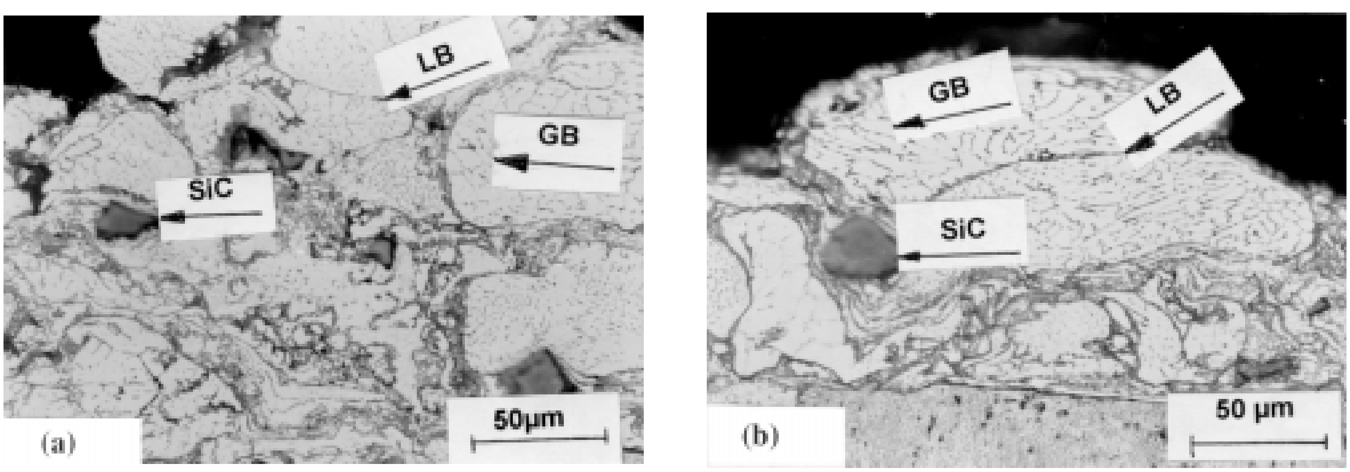

Fig. 4 Optical micrograph of the polished and etched cross sections of the samples HVOF sprayed from a distance of 150 mm with the powder No. 1 (powder composition Al + 15SiC, reinforcement size 30 μm) (a) after spraying and (b) after laser shock treatment. SiC, reinforcement of SiC; LB, boundary between lamellae; GB, boundary between the grains

value is an average of the 15 individual measurements. The laser shocks hardened the coatings (Fig. 6)

The microhardness of the Al + 15 SiC samples was greater for the coatings sprayed using coarse 30 μm SiC grains than for those sprayed using fine 3 μm SiC grains. This effect was even more pronounced for the laser treated samples.

The roughness of the composite coatings does not depend on the spraying distance. The data for the 150 mm spray distance are depicted in Fig. 7.

The least rough among the as-sprayed deposits are the coatings sprayed with powder No. 5 (chemical composition Al + 50 SiC; reinforcement size 3 μm). The LSP treatment reduced considerably the coating roughness. This reduction was related to the plastic deformation of the ductile aluminum matrix by these shocks (Fig. 2). The oscillating wear resistance of the composites did not depend on the spray distance, and the wear, as defined by the parameter w_L, increased after the LSP treatment (Fig. 8).

In fact, some of the treated composite coatings (e.g. those sprayed using powder No. 1 and 3) exhibited wear resistances similar to pure aluminum, which was taken as the reference material.

To explain the results of the oscillating wear, one must remember that the compressive stresses created by the shocks introduced microstructural defects near to the coating surface (as indicated by x-ray peak broadening). These defects could have promoted the creation of fissures that initiated the creation of wear debris. The abrasive action of this debris could have accelerated the surface wear.

4. Discussion

The applied laser power density of 5 GW/cm^2 and the pulse duration of 10 ns corresponded, for the laser system used, to a pressure inside the spot equal to about 4 GPa (Ref 7). This pressure acted, during the laser pulse duration, on the surface of the coating. Consequently, a compressive stress was generated. The stress led to plastic deformation of the ductile aluminum matrix of the coatings. This plastic deformation was confirmed by a slight depression observed in the laser shocked area. A similar phenomenon for polished bulk metal was observed in a previous study (Ref 6).

Other results were specific for the sprayed deposits. First, a decrease of roughness in the coatings contrasted to an increase observed for bulk titanium (Ref 4). This effect could be explained by a leveling of surface asperities by the laser shocks. A second aspect of the present study related to the lack of residual stress in the coatings. In fact, other studies for bulk metals (Ref 4, 7) mention that residual stress results from laser shocks. Another method would be required to confirm the present observation (e.g. a hole drilling strain gauge technique) (Ref 12). If

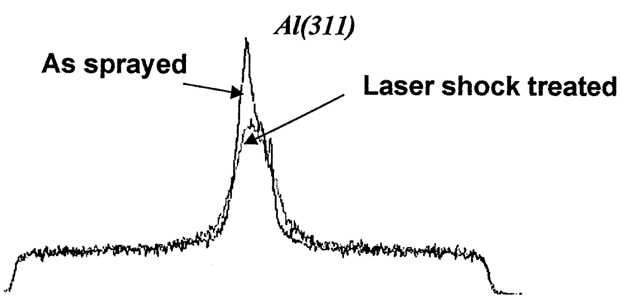

Fig. 5 Al (311) peaks of the sample HVOF deposited from a standoff of 200 mm with a powder No. 5 (composition Al + 50SiC, reinforcement size 3 μm) after spraying and after laser shock treatment. X-ray wavelength was 0.22897 nm and a value of ψ = 60

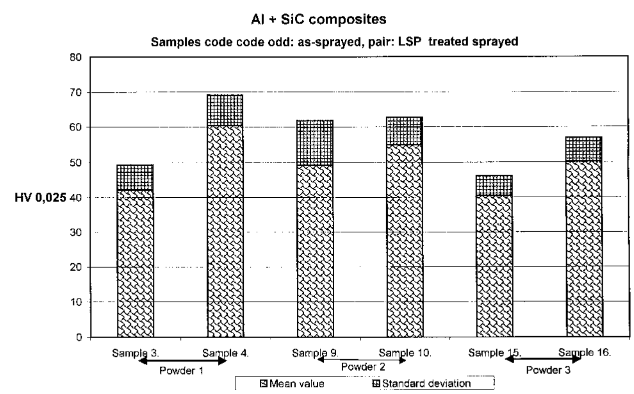

Fig. 6 Microhardness of the aluminum matrix in the composites HVOF deposited from a distance of 200 mm with the powders No. 1, 2, and 3 before and after laser treatment

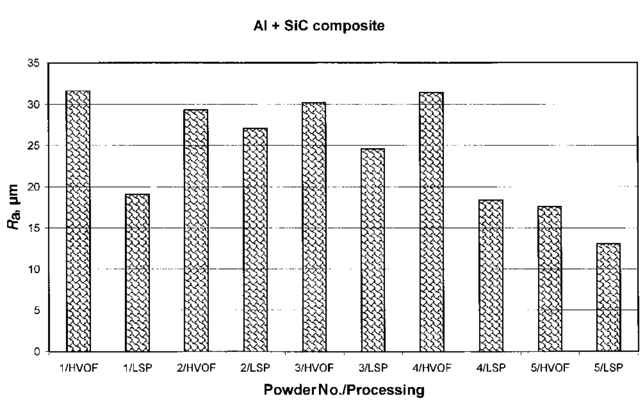

Fig. 7 Roughness (R_a) in μm of HVOF deposited and laser shock treated Al + SiC composite coatings sprayed with different powders and from the spraying distance of 150 mm

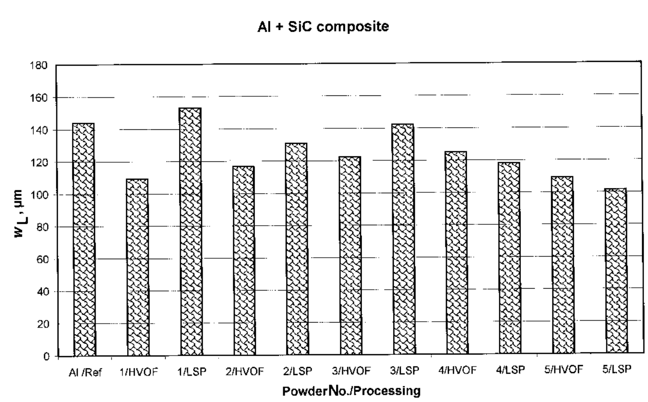

Fig. 8 Oscillating wear resistance w_L in mm of HVOF sprayed and laser shock treated Al + SiC composite coatings sprayed with different powders from the distance of 150 mm

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confirmed, the probable reason for this effect could be related to the ductility of the matrix (the residual stress could be relaxed by plastic deformation of the aluminum). To confirm this hypothesis, a composite with a less ductile matrix should be processed with LSP, and the stresses should be checked. On the other hand, the laser processing densified the matrix, increased its microhardness (similar to that of the metal studied in Ref 4), and improved the contact between the SiC reinforcement and the matrix (Fig. 4). The broadening of the x-ray peaks in the LSP treated coatings was related to generation of the microstructural defects and was also observed in other studies (Ref 4).

The sliding wear resistance of the laser shocked coatings was less beneficial than that of the as-sprayed samples. A possible explanation is the generation by laser shocks of high concentration of structure defects near the surface. These defects could have resulted in crack formation during the sliding wear resistance test. Such fractures would grow under the pressure of the sliding sphere. Subsequently, a part of the coating could detach and transform into debris. The debris that was initially composed of aluminum could oxidize to form Al_2O_3. Hard particles of alumina and silicon carbide could act as an abrasive medium and accelerate the wearing.

5. Conclusions

The Al + SiC particulate composite coatings were HVOF sprayed using five powders of different reinforcement sizes and chemical compositions. The coatings were submitted to the LSP technique and an oscillating wear test.

- The test showed that the as-sprayed coatings deposited with the powders of 30 μm reinforcement size exhibited the best wear resistance.
- The LSP modified the morphology of the sprayed coatings. The surfaces became smoother and the coatings were less porous.
- In particular, the contact between the aluminum matrix and the SiC reinforcement was enhanced. However, the wear of laser processed coatings was greater than the wear of as sprayed ones. This might be tentatively explained by the formation of microstructural defects that could promote crack generation such that the resulting debris would accelerate coating wear. Further investigations of the microstructure with transmission electron microscopy are necessary to confirm this explanation. On the other hand, the effect of an application of less ductile matrix material on the laser treated material should be studied.
- Finally, the fact that residual stresses were not found in the laser treated coatings should be verified with another method than that applied in the present study.

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