JTTEE5 23:750–754
DOI: 10.1007/s11666-014-0067-4
1059-9630/$19.00 © ASM International

Technical Note

Laser Remelting of Plasma-Sprayed Tungsten Coatings

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(Submitted September 24, 2013; in revised form January 17, 2014)

Laser surface melting was applied on plasma-sprayed tungsten coatings, with the aim to eliminate intersplat voids and improve thermal conductivity. A variety of laser parameters was tested and the morphology and melt depth were evaluated. With the most promising conditions, 2D areas were remelted and thermal conductivity was determined. Improvements in conductivity were observed, but the depth of the remelted layer was quite limited under current conditions. Advantages and limitations of this method, as well as possible directions for improvement are discussed.

Keywords functionally graded coatings, laser remelting, plasma facing materials, thermal conductivity, water stabilized plasma

1. Introduction

Laser surface melting is a post-treatment technique with the potential to improve the properties of thermally sprayed coatings. These coatings inherently contain a large number of voids, cracks, and unbonded interfaces, which, even at a relatively small volume fraction, reduce their mechanical and thermal properties, such as hardness, Young's modulus, thermal conductivity, etc. (Ref 1). With surface remelting, these imperfections can be eliminated in the affected zone. In several case studies, this has been shown to reduce the porosity and surface roughness, homogenize the composition, and improve the hardness, modulus, adhesion strength, wear resistance, and thermal shock resistance of particular systems (Ref 2-8).

This paper focuses on the application of laser remelting on plasma-sprayed tungsten coatings. Tungsten is the main candidate material for plasma facing components of future nuclear fusion reactors (Ref 9, 10). While plasma spraying offers several advantages for this application, as discussed in Ref 11, the reduced thermal conductivity appears to be a major hindrance toward application in areas with high heat fluxes (Ref 12). Among the post-treatment techniques for conductivity improvement, laser remelting has been tested. The encouraging results from a small-scale initial study (Ref 13) prompted the investigation presented in this paper.

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2. Experimental

Tungsten coatings were produced by water stabilized plasma spraying, with the following parameters: WSP-500 torch (Institute of Plasma Physics, Prague, Czech Republic), power 160 kW, feeding distance 25 mm, spraying distance 250 mm, powder feed rate 540 g/min, carrier gas argon, 5:1 mixture of W powder 63-80 µm (Alldyne Powder Technologies, Huntsville, USA) and WC powder 40-80 µm (Osram, Bruntál, Czech Republic), coating thickness ~1 mm. The coating surfaces were ground by a sandpaper, to achieve a uniform surface. For the initial set of laser experiments, plain carbon steel substrates 2.5 mm thick were used. For the subsequent sets, 20 mm copper substrates were used, to have conditions closer to realistic dimensions of plasma facing components. The laser treatment was performed on an HL 703 D type Nd:YAG continuous laser (Trumpf, Ditzingen, Germany) with a wavelength of 1064 nm and maximum power of 700 W. The following parameters were varied: laser spot diameter (controlled by the position of the focus with respect to sample surface), traverse velocity and track spacing during 2D scanning. Nitrogen jets around the laser head were applied to prevent oxidation of the heated surface.

In order to facilitate better insight and quantitative assessment of the influence of different parameters and their combinations, the engineering variables mentioned above were converted to physical variables as follows:

$$\text{power density: } q = \frac{4P}{\pi d^2}$$

$$\text{energy density: } e = qt = q\frac{d}{v} = \frac{4P}{\pi dv}$$

$$\text{thermal penetration: } T = 2\sqrt{\chi t},$$

where P is the laser power, d the laser spot diameter, v its traverse velocity, t is time the laser remains on a selected point and χ is thermal diffusivity of the treated material

(Ref 14). For χ, a value of 0.07 cm^2/s, typical for plasma-sprayed W coatings, was used (Ref 15).

The treated specimens were observed in a scanning electron microscope (4DV, CamScan, Cambridge, UK and EVO MA15, Carl Zeiss, Oberkochen, Germany). Width and surface morphology (contiguity, smoothness, presence of oxides) of the laser-remelted tracks was characterized, as well as depth of the remelted layer. The latter was determined as the maximum depth in the center of a crescent-shaped cross-section of the remelted track, sufficiently distant from the track ends. Thermal diffusivity of as-sprayed and selected 2D-treated specimens was determined on an FL-3000 (Anter Corp., Pittsburgh, USA) instrument.

3. Results

In the first stage, a broad range of experimental conditions was explored, applying single laser tracks. The results are summarized in Table 1. Examples of surface morphology are shown in Fig. 1. The resulting surface modification ranged from nearly no remelting to contiguous melt pool to a melt-through with material ejected from the entire tungsten layer. These are labeled in the last column of Table 1. The goal was to achieve a contiguous and smooth melt pool and as high as possible depth of the remelted layer. The successful runs from this point of view are those marked ''CS'' in Table 1. The maximum remelted depth was about 500 μm in run #18. The results indicated that to achieve significant melting, slower laser motion and smaller laser spot are beneficial.

In the second stage, a large number of parameter combinations from a narrower window, suggested by the first stage results, were tested on coatings sprayed on a copper block. The laser spot diameter was varied from 0.3 to 0.67 mm and traverse velocity from 5 to 150 mm/min. In all of these cases, smooth and contiguous melt pool was achieved (Fig. 2a). The remelted depth varied from 150 to 320 μm. Three highest values together with the experimental conditions are presented in Table 2. The maximum value is smaller than the one achieved on thin steel substrates, despite generally increased energy density. This can be explained by the copper acting as a heat sink (with higher thermal conductivity as well as mass) that draws the heat from the surface-heated tungsten layer faster than the thinner steel substrate. There was a noticeable correlation between the remelted depth and the thermal penetration, although not very tight (Fig. 3). Probably some local variations in the coating structure may have influenced the heat conduction conditions. Similar plots, with a slightly weaker correlation, were obtained also for the energy density and total energy deposited into the track. No clear trend was observed for the remelted depth versus power density. Expectedly, the width of the remelted layer correlated quite well with the laser spot diameter (Fig. 4a). While at this stage it was not an optimization criterion, the track width becomes an important parameter in 2D scanning, with respect to track overlapping. Since the experiments were not performed on a dedicated instrument, the nitrogen jets did not provide a perfect protection against oxidation; therefore, small amount of oxides were observed on the surface in some cases (Fig. 2b). The degree of oxidation was assessed only semi-quantitatively and was found to roughly correlate with the laser spot diameter (Fig. 4b).

In the third stage, 2D scanning was performed to remelt a significant area of the surface. Traverse velocity was varied only between 6 and 10 mm/min, laser spot diameter between 0.55 and 0.67 mm, span between adjacent tracks was varied between 0.1 and 0.5 mm. Examples of overlapping tracks are shown in Fig. 5. It was found that

Table 1 Overview of the first stage experiments—processing conditions and results

Run #	Spot diameter, mm	Traverse velocity, mm/min	Track spacing, mm	Power density, W/mm^2	Energy density, J/mm^2	Total energy, J	Thermal penetration, mm	Melt width, μm	Melt depth, μm	Result
1	0.42	1000	…	5053	127	420	0.03	…	0	I
2	0.87	1000	…	1178	61	420	0.04	530	0	I
3	0.87	1000	…	1178	61	420	0.04	470	0	I
4	0.87	500	…	1178	123	840	0.05	570	0	I
5	0.87	200	…	1178	307	2100	0.09	660	100	P
6	0.87	50	…	1178	1229	8400	0.17	700	150	P
7	0.87	20	…	1178	3073	21,000	0.27	850	220	C
8	0.87	20	…	1178	3073	21,000	0.27	860	240	C
9	0.67	20	…	1985	3991	21,000	0.24	790	186	CS
10	0.48	20	…	3868	5570	21,000	0.20	…	1500	O
11	0.48	50	…	3868	2228	8400	0.13	660	176	CS
12	0.42	70	…	5053	1819	6000	0.10	…	1500	O
13	0.42	150	…	5053	849	2800	0.07	610	155	CS
14	0.42	100	…	5053	1273	4200	0.08	570	176	CS
15	0.42	100	0.4	5053	1273	4200	0.08	535	145	CS
16	0.42	100	0.2	5053	1273	4200	0.08	530	168	CS
17	0.42	100	0.2	5053	1273	4200	0.08	565	220	CS
18	0.67	20	0.2	1985	3991	21,000	0.24	1030	500	CS

In the last column, labels representing qualitatively the results are: *I* insufficient melting, *P* partial melting, *C* contiguous melting, *CS* contiguous and smooth melting, *O* overmelting

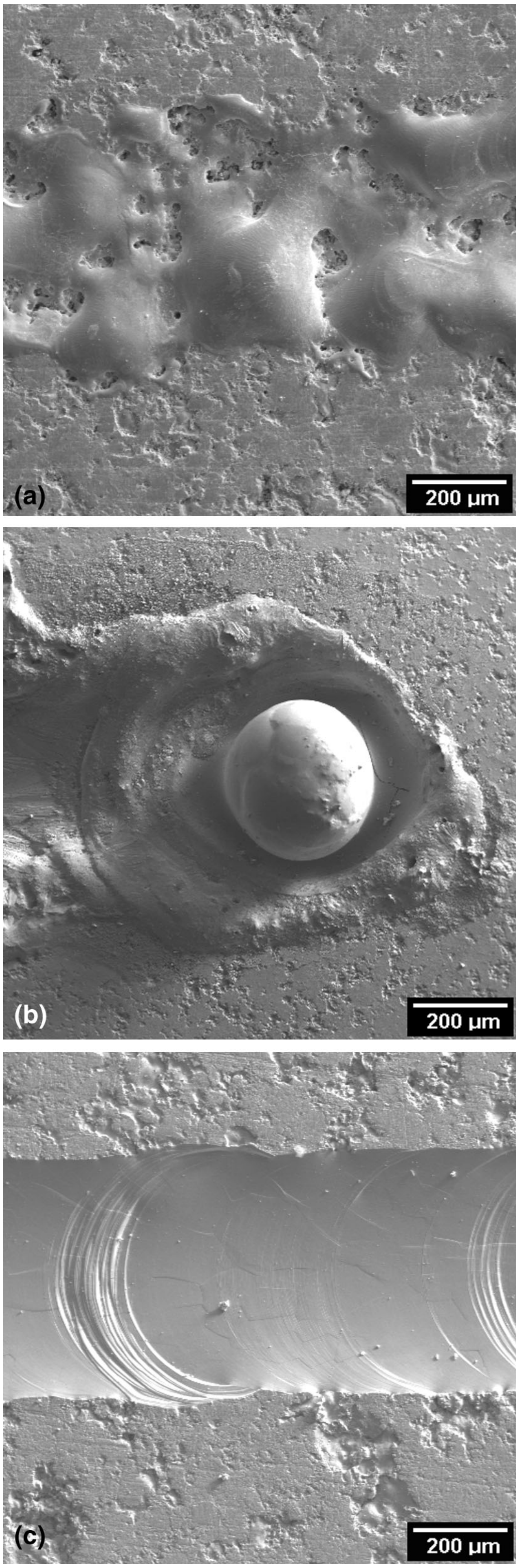

Fig. 1 Surface appearance of single laser tracks. Example of (a) insufficient melting (run #4), (b) overmelting (run #12), and (c) optimal melting with smooth and contiguous melt pool (run #14)

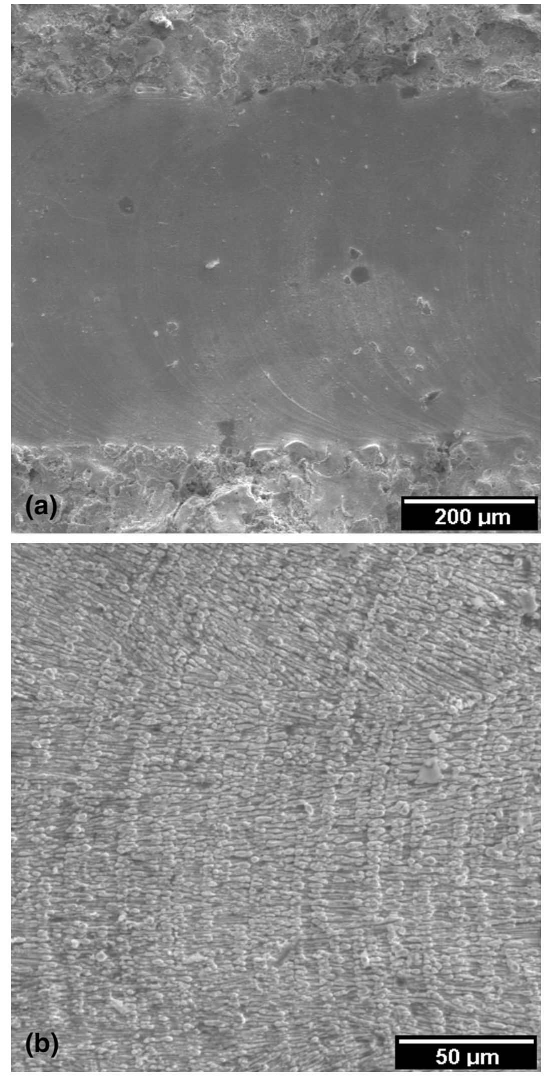

Fig. 2 (a) Example of a smooth and contiguous molten track ($d = 0.42$ mm, $v = 100$ mm/min); (b) detail of a slightly oxidized surface ($d = 0.55$ mm, $v = 50$ mm/min)

at spacings 0.4 mm and above, much smaller remelted depth was obtained at the boundary between the tracks; track spacings 0.3 mm or smaller were needed to achieve a significant melt depth throughout the treated area. In several instances, the coating was ground to lower thickness (0.8, 0.5, and 0.3 mm) and laser spot diameter further reduced to 0.3-0.5 mm, in an attempt to melt the entire thickness of tungsten layer down to the interface. However, the maximum achieved melt depth was about 2/3 of the tungsten thickness. Apparently, the higher proximity of the copper substrate to the heated surface enhanced the heat dissipation and hindered complete melting.

Thermal diffusivity of a laser-remelted sample ($d = 0.42$ mm, $v = 10$ mm/min, track spacing 0.25 mm) was measured and compared with that of an as-sprayed coating. The results are presented in Table 3. On average, a 2.3× increase was observed.

Table 2 Selected results from stage 2 with the highest achieved melt depth

Spot diameter, mm	Traverse velocity, mm/min	Power density, W/mm^2	Energy density, J/mm^2	Total energy, J	Thermal penetration, mm	Melt width, µm	Melt depth, µm
0.55	8	2946	12,154	52,500	0.34	687	319
0.67	10	1985	7982	42,000	0.34	716	309
0.3	8	9903	22,282	52,500	0.25	627	281

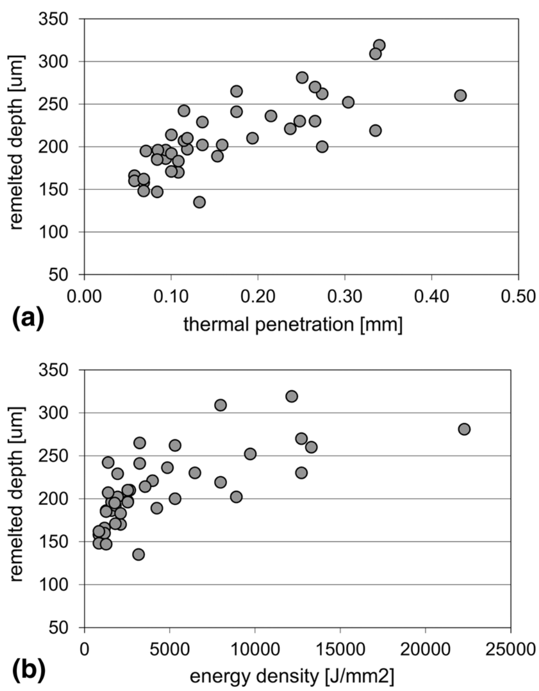

Fig. 3 Correlation between remelted depth and (a) thermal penetration and (b) incident energy density. Data from 43 runs from stage 2

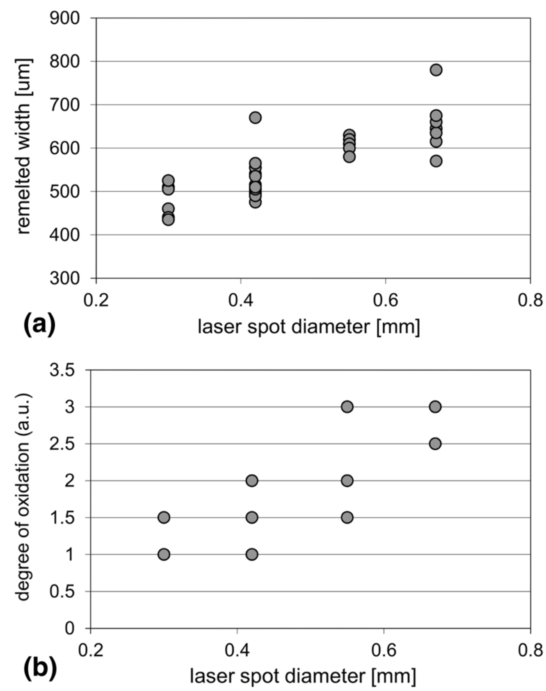

Fig. 4 Correlation between (a) remelted width, (b) degree of oxidation and laser spot diameter. Data from 43 runs from stage 2

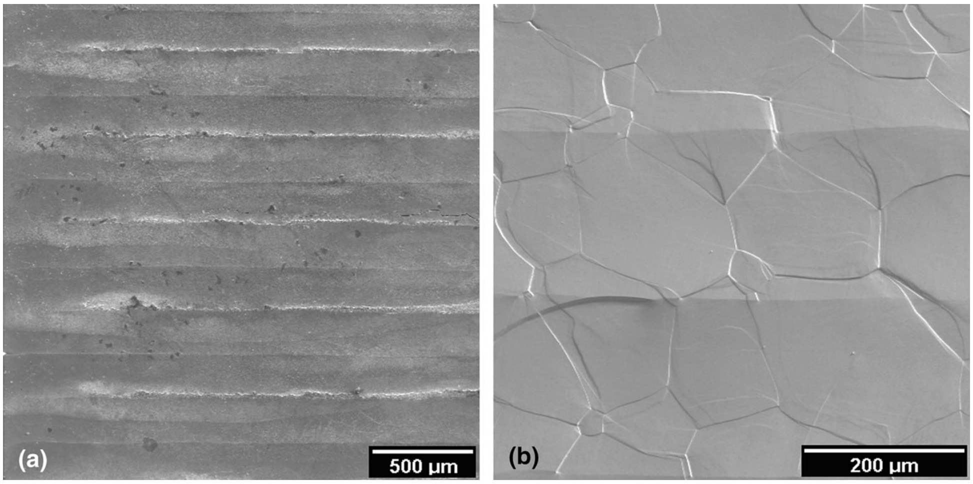

Fig. 5 Examples of 2D scanning with parallel overlapping tracks: (a) overview ($d = 0.42$ mm, $v = 50$ mm/min, track spacing 0.2 mm); (b) detail with enhanced grain boundaries, resulting from slow resolidification of molten tungsten ($d = 0.42$ mm, $v = 100$ mm/min, track spacing 0.2 mm)

Table 3 Comparison of thermal diffusivity of as-sprayed and remelted tungsten coating

	Thermal diffusivity, cm^2/s	
Temperature, °C	As-sprayed	Remelted
100	0.060	0.160
200	0.060	0.142
300	0.059	0.128
400	0.058	0.121

4. Conclusions

In this work, laser remelting was applied on plasma-sprayed tungsten coatings with the goal of increasing their thermal conductivity. Among the parameters varied were the laser spot diameter, traverse velocity and track spacing. It was found that the remelted depth correlated most with thermal penetration (which is directly connected to traverse velocity) and incident energy density (connected both to traverse velocity and spot diameter). A clear improvement in thermal conductivity of the tungsten coatings was demonstrated. The remelted depth was typically 300 μm or less. While the incident laser energy was—in most cases—more than sufficient to melt the entire coating thickness, part of it was lost due to reflection from the surface and part through heat dissipation into the surrounding material. As the experiments were performed on a non-dedicated facility, there is room for further process optimization. Possible improvements (i.e., melting of a higher volume) can be expected from the following:

- higher power laser
- laser with a different wavelength (the reflectivity of tungsten at 10 μm is 0.98, at 1 μm is 0.58 (Ref 16))
- usage of a vacuum or inert gas chamber that would eliminate oxidation and enable higher workpiece temperatures.

In summary, laser remelting is a prospective post-treatment technique, capable of efficiently increasing thermal conductivity of plasma-sprayed coatings. Its main advantages lie in the following points: it is a mini-invasive technology; with its localized surface heating it provides minimal heat input to the bulk of the part. Unlike other densification methods, mentioned in Ref 13, it is applicable to real parts, without any strict limitations on size and shape, thereby preserving the main advantages of plasma spraying.

Acknowledgments

This work has been carried out within the framework of the Integrated European Project ''ExtreMat'' (contract NMP-CT-2004-500253) with financial support from the European Community. It reflects the views of the authors only and the European Community is not liable for any use of the information contained herein. Financial support from the Czech Science Foundation though grant no. P108/12/1872 for the final characterization is also acknowledged.

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