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ORIGINAL PAPER

Characterization of Laser Remelted Plasma-Sprayed Mo Coating on AISI 1020 Steel

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Abstract Plasma-sprayed molybdenum (Mo) coating was deposited on an AISI 1020 steel substrate. Laser remelting was used to eliminate the open pores and microcracks of the plasma-sprayed molybdenum coating. The quantitative investigation of porosity was carried out with the help of *Biovis* image analysis software. The microhardness was measured using a Vickers indenter. The influence of laser remelting on the wear volume loss of plasma-sprayed Mo was estimated by using a pin-on-disc wear test rig. The worn surface was characterized by scanning electron microscopy. The experimental results demonstrate that the porosity of the coating was decreased and microhardness was improved by laser remelting. The laser remelted plasma-sprayed Mo coating exhibits better wear resistance compared to the untreated plasma-sprayed Mo coating. It is concluded that laser remelting is a potential treatment for the plasma-sprayed coating. In this study, the laser remelted plasma-sprayed Mo coating exhibited of lowest porosity, higher hardness and better wear resistance.

Keywords Laser remelting · Wear · Plasma spray · Molybdenum

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1 Introduction

Given the ability to deposit a different kind of coating material and ease of application, the plasma-spraying coating technique is generally employed to fabricate wear resistant coatings. However, the properties of the plasma-sprayed coatings can be restricted by the presence of microstructural defects, such as high porosity, weak interconnection between splats and a considerable lack of chemical homogeneity. The porosity, in particular, can reduce the wear resistance and corrosion resistance because it provides channels of penetration through which aggressive media reach the substrate [1, 2].

Laser treatment is a promising way to improve wear performance of the sprayed coating. The laser treatment may contribute to the elimination of porosity, enhancement of the coating strength and chemical homogeneity, as well as the development of a metallurgical bonding at the coating–substrate interface producing strengthened coating adhesion [3–5].

Guozhi et al. [2] investigated the corrosion properties of plasma-sprayed (PS) Ni-coated WC coatings both before and after laser remelting of the coatings. The investigation revealed that coatings with laser remelting could improve their microstructure, such as lower porosity rate, weaker lamellar structure and more uniform distribution of phases. Wang et al. [6] studied the laser remelting of plasma-sprayed nano-structured Al_2O_3–TiO_2 coatings at different laser powers. They reported that laser remelting produces a denser and more homogenous structure as well as an outstanding metallurgical bonding between coating and substrate. Li et al. [7] studied the effects of laser remelting on the microstructure, phase composition and mechanical properties of ceramic coatings. The results clearly demonstrated that laser remelting is suitable for the fabrication of dense Al_2O_3–13 wt.% TiO_2 coatings on AZ91D magnesium alloy. They concluded that as-sprayed coatings exhibit a unique bimodal microstructure consisting of a fully melted region and a partially melted region. The remelted coatings possess an excellent metallurgical bonding to the substrate without interfacial porosity. Pre-existing defects and lamellae structure of the as-sprayed coatings were eliminated after laser remelting and a more compact and homogenous structure was obtained. Wang et al. [8] studied the effects of laser remelting on the microstructure of nanostructured Al_2O_3–13 wt.% TiO_2 ceramic coatings prepared by plasma spraying with agglomerated powders. The study revealed that the lamellar defect of the as-sprayed coating is erased, and the compactness of the coating is improved significantly after laser remelting. Wang et al. [3] investigated the effects of laser power on microstructure and properties of the laser remelted Al_2O_3–13 wt.% TiO_2 coatings. They concluded that laser remelting produces a much denser and more homogenous structure as well as an excellent metallurgical bonding to the substrate. The microhardness of the laser remelting was enhanced to 1200–1800 $HV_{0.3}$, which was much higher than that of the as-sprayed coatings and 3–5 times that of the substrate.

Serres et al. [9] investigated the mechanical properties and wear resistance of laser remelted NiCrBSi coatings. The result demonstrated that the remelted samples had better mechanical performances than as-sprayed coatings. In addition, the adhesion of remelted samples was strongly increased. Garcia et al. [10] studied the tribological behaviour of NiCrBSi plasma spray coatings partially melted by laser. The results of wear tests indicated that the wear rate was reduced by 46% for the laser melted area. Szkodo and Bie [5] compared the tribological and mechanical properties of the laser remelted coatings with the tribological and mechanical properties of the "as-sprayed" coating. The study showed an improvement of the mechanical and tribological properties caused by the laser treatment. Fernanciez et al. [11] investigated the effects of laser treatment on the wear behavior of plasma-sprayed Al_2O_3 coatings. They reported that better wear resistance was obtained after laser treatment of the ceramic coating. Liang et al. [12] studied wear resistance of plasma-sprayed and laser remelted coatings on aluminum alloy. The experimental results showed that the laser treated plasma-sprayed samples demonstrated good wear resistance.

Hence, the study of the available literature validates that the laser remelting can improve the wear resistance of the coating. In view of this, the current work presents dry sliding wear behaviour of laser remelted plasma-sprayed Mo coatings.

2 Experimental Details

2.1 Materials

In the present study, the materials used for coating are commercially available molybdenum (Mo) powder with a particle size varying from 15 μm–40 μm and AISI 1020 steel as a substrate material. The AISI 1020 steel is extensively used for a variety of general engineering and construction applications such as pins, chains, shafts, hard wearing surfaces, axles and automobile parts. The AISI 1020 steel was prepared as a pin with a size of 10 mm diameter and 30 mm height.

2.2 Plasma Spraying

Molybdenum coating with a thickness of 300 μm was deposited on AISI 1020 steel by atmosphere plasma spraying (ALT-F 3MB). The plasma gas was argon (Ar) + 20 to 25 vol.% hydrogen (H_2). The coating powder material was supplied vertically into the plasma jet by argon (Ar) carrier gas for primary flow and hydrogen (H_2) for secondary flow. The plasma spraying was performed with a parameter combination shown in Table 1. Before spraying, the substrate surface was grit-blasted to improve adherence.

2.3 Laser Remelting Process

The laser remelting of plasma-sprayed Mo coatings was carried out using a 75 W, Nd: YAG Laser and the setup is shown in Fig. 1. The laser process parameters used for remelting are shown in Table 2. The sample surface was protected by argon gas during laser scanning.

2.4 Experimentation

The wear performance of laser remelted samples and plasma-sprayed Mo coatings was tested using a pin-on-disc wear test rig (Ducom: model TR-20LE) shown in Fig. 2. The tests were conducted as per ASTM G99 standards. The normal load was applied on the pin by a dead weight through a pulley string arrangement. The system had a maximum load capacity of 100 N. The rotational speed of the disc was 0-2000 rpm. The disc is made of En-32 steel (0.14% C, 0.18% Si, 0.52% Mn, 0.015% S, 0.019% P, 0.13% Ni, 0.05% Cr, 0.06% Mo, balance Fe), having dimensions of 160 mm diameter and 8 mm thickness with a hardness value of HRC62. By using an electronic weighing machine, the initial weight of the specimen was measured. The wear tests are performed by sliding the coated pin against the disc, under dry conditions by varying the applied load, sliding

Table 1 Process Parameters selected for Plasma Spraying

Parameters		Range
Plasma system Gun		ALT-F 3MB
Plasma gases	Pressure (N/mm^2) − Argon & Hydrogn	0.689−0.827
	Flow rate (m^3/ min) − Argon	2.26 − 2.54
	Hydrogen	20 − 25
Power	Current(A)	490
	Voltage(V)	70
Powder feed rate (gms/min)		40−50
Spraying conditions	Nozzle diameter(mm)	8
	Spraying Distance(mm)	75 − 125

speed and sliding distance. After completion of the wear test, the specimen was cleaned with acetone to remove any debris present on the worn surface. The final mass of the specimen is measured. By using the coating density, the mass loss is converted into wear volume loss. The wear volume loss of the coatings was studied as a function of the applied load, sliding speed and sliding distance. The wear resistance of the coatings was studied as a function of the applied load, sliding speed and sliding distance. The wear debris and worn surface of test specimens were analyzed by Scanning Electron Microscopy (SEM) (JEOL 6830 SEM) to understand the wear mechanism.

3 Results and Discussion

3.1 Effect of Laser Treatment on the Morphology and Porosity of Coatings

3.1.1 Morphology

Figure 3a shows a SEM image of the top surface of the plasma-sprayed Mo coating. The plasma sprayed Mo coating surface is consists of unmelted, partially melted and fully melted splats. The surface also comprises a large number of microcracks. Figure 3b illustrates a cross-sectional micrograph of the plasma-sprayed Mo coating and it depicts the lamellar microstructure of the coating. The micropores and other defects can also be observed in Fig. 3b. The existence of these microstructural imperfections reduces the density of the coating and the adhesion.

Figure 4a and b shows the morphology of the plasma-sprayed Mo coating after laser remelting. Figure 4a confirms that the unmelted, partially melted splats shown in Fig. 3a were effectively remelted by the laser. However, a network of microcracks is observed on the laser remelted surface. The microcracks originate due to shrinkage and thermal stresses that occur during the rapid cooling after laser remelting. Figure 4b is a cross-sectional image of the plasma-sprayed Mo coating after laser remelting. The reduced number of micropores and other structural imperfections can be observed. From Fig. 4c it is confirmed that lamellae of the coating were remelted effectively by laser remelting.

Fig. 1 Laser setup

Table 2 Selected laser process parameters for remelting of plasma-sprayed Mo coatings

Parameter	Range
Power (W)	75
Laser Scanning Speed (mm/s)	128
Pulse Frequency (khz)	35
Pulse width (μs)	25
Argon gas flow (l/min)	12
Travel speed (mm/sec)	4
Focal setup	Focused laser beam
Wave length (nm)	1060 – 1070

Fig. 2 Dry sliding wear test rig

3.1.2 Porosity

In this work, porosity measurement was done by using the image analyser. In this technique, a cross-section coated sample was polished and examined in an inverted microscope equipped with a CCD camera and analyzing software. The image was analyzed using Biovis image analysis software as per the American Society for Testing and Materials (ASTM) 296B standard. The total area captured by the objective of the microscope or a fraction can be accurately measured by the software. Hence the total area and the area covered by the pores are separately measured and the surface porosity determined.

The level of porosity quantified by the image analyser is very much reduced after laser remelting, decreasing from 10.84% to 1.34%. The reduction in the level of porosity is mainly due to remelting of the coating. The laser remelting enhances the densification of the structure and permits a larger quantity of pores in the sprayed coating to join together and escape.

3.2 Microhardness of Laser Treated and Plasma-Sprayed Coating

Figure 5 shows that the microhardness of the laser remelted coatings is higher compared to that of the plasma-sprayed coatings. After laser treatment, a graded distribution of hardness in the coating can be attributed to the formation of three regions such as the remelted zone, the heat affected zone and the substrate as can be seen in Fig. 4b. The enhancement of microhardness is mainly due to the melting layer becoming much denser; pores and other defects are substantially reduced or even eliminated after laser treatment. Similar results were observed by Liang et al. [12] and Yuanzheng et al. [13].

3.3 Dry sliding Wear Behaviour of Laser Remelted and Plasma-Sprayed Mo Coating

3.3.1 Effect of Load on Wear Volume Loss

The wear data shows (Fig. 6) that the volume loss increases with increasing load, but the rate of volume loss of the plasma-sprayed coating with increasing load is much higher than that of the laser remelted coating. The volume loss of the plasma-sprayed coating is about four times greater than that of the laser remelted coatings with a load of 10 N. Under a load of 50 N, the volume loss of plasma-sprayed coating is three times as high as that of the laser remelted coatings and similar results were observed by Fu et al. [14]. It is observed that the laser treatment can improve the wear resistance of the plasma-sprayed Mo coating significantly. This is because of an improvement in bonding strength and a significant decrease in porosity after laser treatment. The minor changes in hardness and surface roughness of the laser treated coating contribute an enhancement in wear resistance.

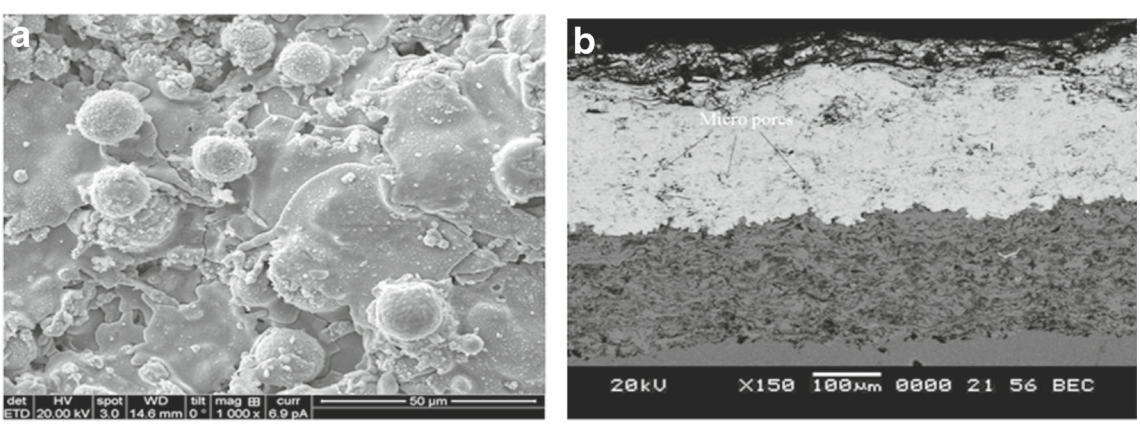


Fig. 3 Plasma-sprayed molybdenum coating before laser remelting (**a**) top surface (**b**) cross-section of coating

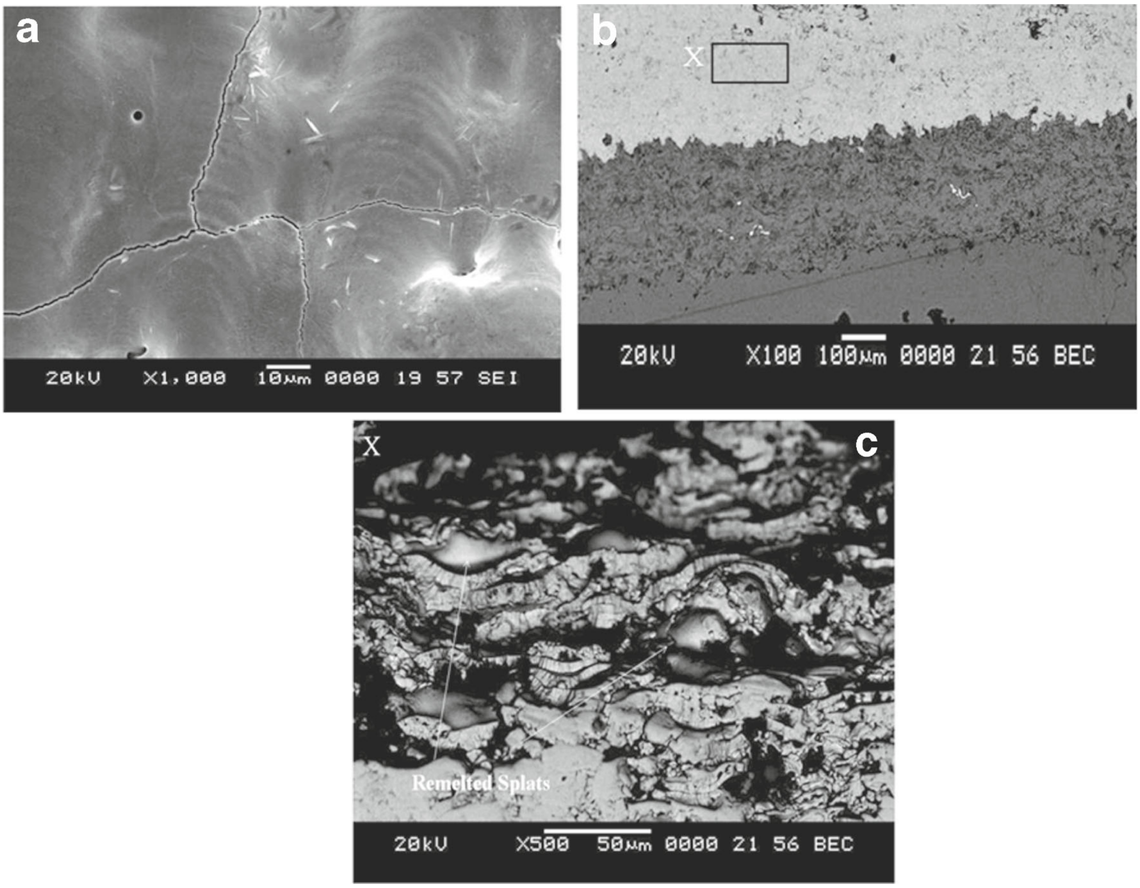
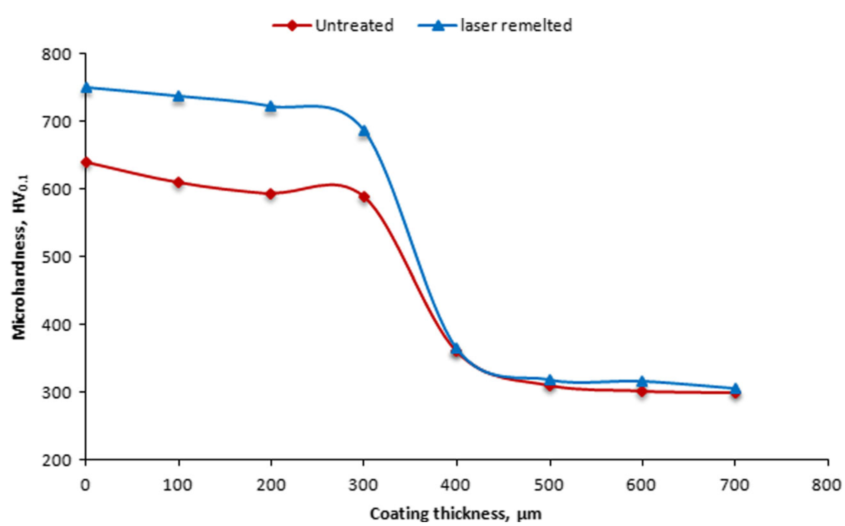


Fig. 4 Plasma-sprayed molybdenum coating after laser remelting (**a**) top surface, (**b**) cross-section of coating, (**c**) Magnified image (at 500X) of coating cross section

The worn surface of a plasma-sprayed Mo coating is illustrated in Figs. 7–10. From Fig. 7, the spallation of the coating is very much noticeable at its surface. The spallation of the plasma-sprayed Mo coating is due to the collective effects of a huge porosity reduced bonding strength and low ductility. The cracks that exist in the plasma-sprayed coating and new cracks originating in the coating during the sliding wear process propagate rapidly and finally interconnect

Fig. 5 Variation of microhardness with distance from the surface



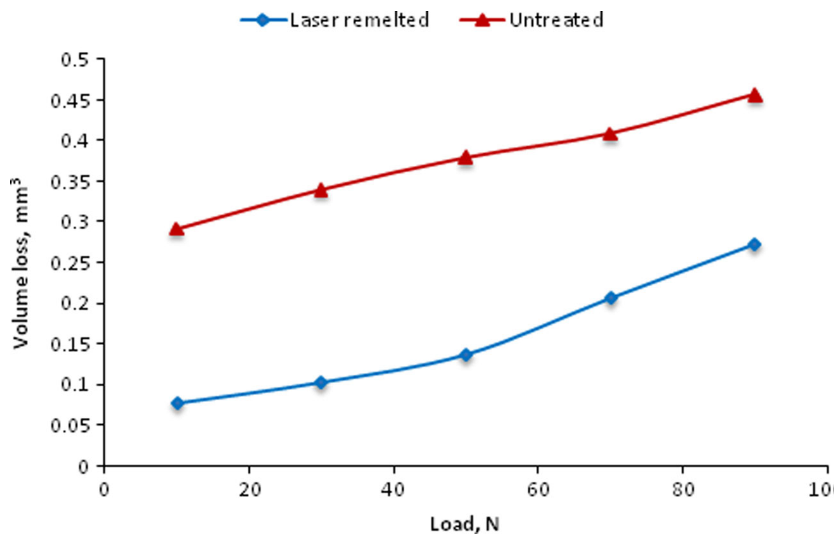


Fig. 6 Effect of load on volume loss

with each other leading to more removal of material from the coating surface. Figure 8 shows the particles which are detached from the coating. The cracks are frequently found to pass through the unmelted particles in the coating; an example is shown in Fig. 9. Figure 10 illustrates detached particles and spalled coating debris that act as hard wear particles which are responsible for the subsequent ploughing of the coating. Therefore, the main wear mechanism for plasma-sprayed coatings is spallation of the coating and abrasive wear mechanism.

The wear behavior of the laser remelted coating is different as compared to the plasma-sprayed Mo coating. Figure 11 illustrates that the worn surface of the laser remelted coating is characterised by ploughing and wear particles which are close to detaching. The severe plastic deformation at the edge of the ploughing track is shown in Fig. 11. It denotes that the sliding wear is caused by high temperature. The molybdenum splats are adjacent to the local contact area which is softened and condensed by plastic deformation.

The spallation of the coating is also noticed in the laser remelted coating surface as shown in Fig. 12, but it is not widespread as compared to the plasma-sprayed Mo coating, although there are cracks in the laser remelted coating. In summary, the main wear mechanisms of laser remelted coatings are ploughing and abrasive wear.

3.3.2 Effects of Sliding Distance on Wear Volume Loss

It is observed from Fig. 13 that the volume loss of both the laser remelted plasma-sprayed coating and untreated

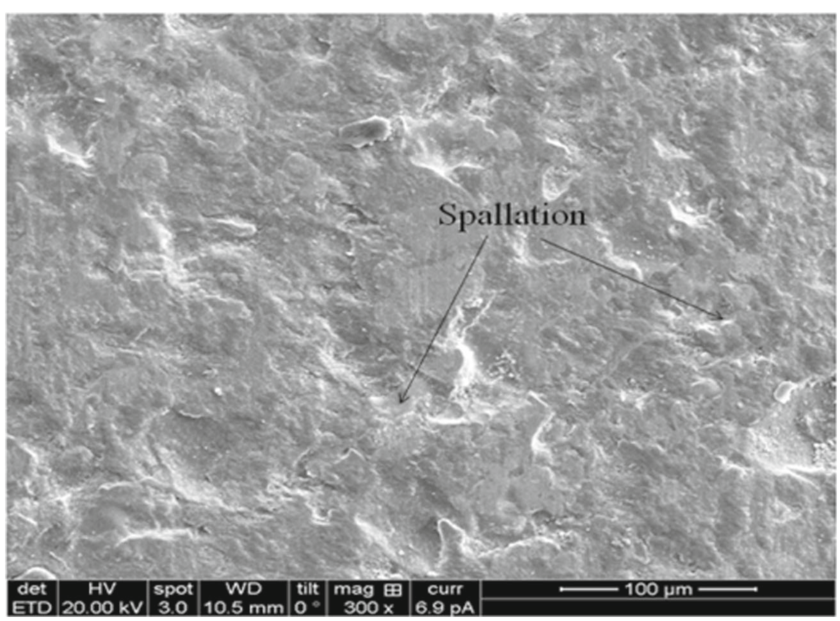


Fig. 7 Worn surface of plasma-sprayed Mo coating showing areas of spallation

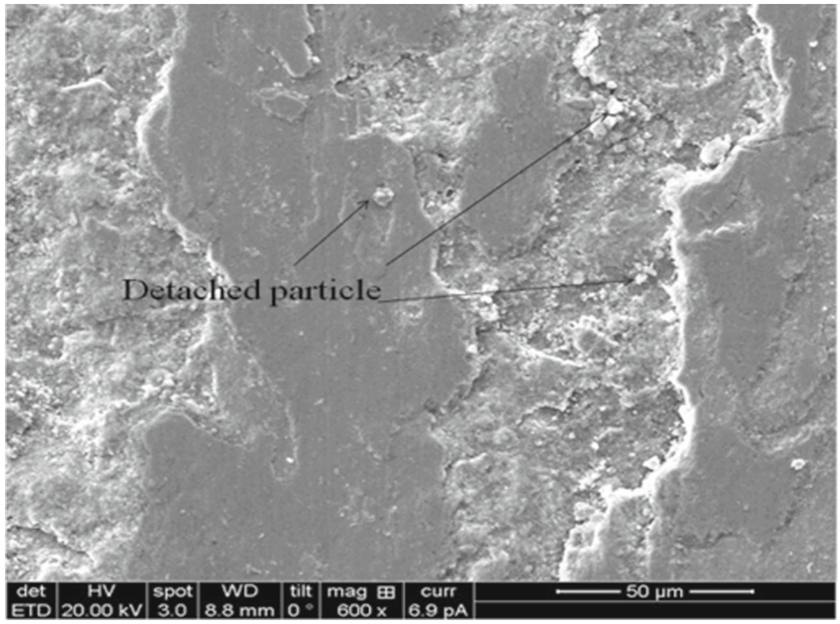


Fig. 8 Detached particles on the worn surface of the plasma-sprayed Mo coating

coating increases with increase in sliding distance. Kato, Das and Khedkar et al. [9–11] also observed a general linear trend of material loss of the sprayed coating increasing with increase in the sliding distance.

Figure 14 shows the worn surface of the laser remelted Mo coating tested at different sliding distances. This SEM micrograph shows that grooves are formed along the sliding direction. This feature is a characteristic of adhesive wear. At lower sliding distance, the hard particles are entrapped between the pin surfaces and the sliding disc. The hard particles cut over the coating surface and the formation of grooves causes wear volume loss as shown in Fig. 14a. These findings agree with the earlier studies [12–14]. The worn surface shows (Fig. 14a and b) that the surfaces are covered by a fine oxide layer. The oxidation of the surface takes place due to frictional heating during sliding. Due to this, a volume loss of coating is less at lower sliding distance and the wear behaviour is oxidative wear [21]. As the sliding distance increases there is a gradual transition in the wear behaviour of the laser remelted coating from an oxidation wear to delamination wear as shown in Fig. 14b. The penetration of hard asperities of the counter-surface to the softer pin surface increases. The deformation and fracture of asperities of the softer surface also increases.

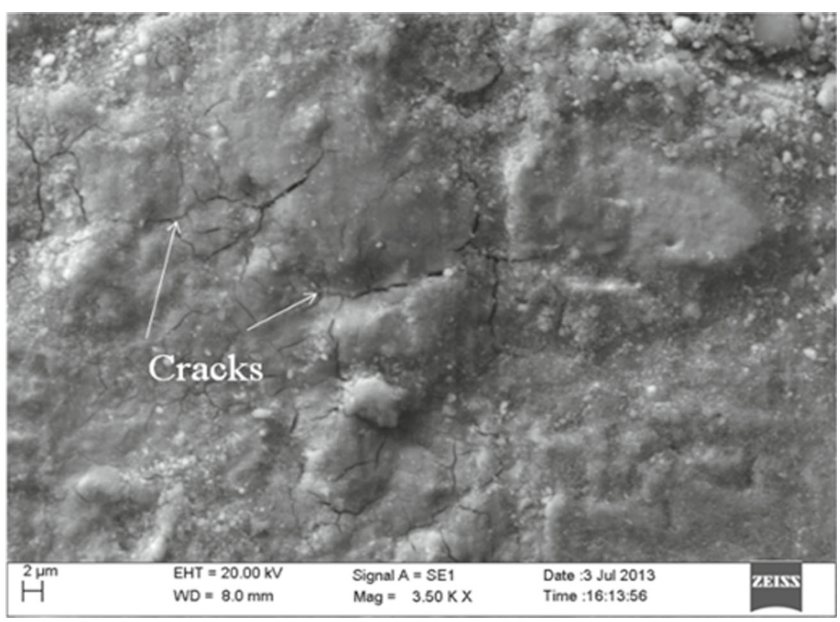


Fig. 9 Crack passing around an unmelted particle on the worn surface of the plasma-sprayed Mo coating

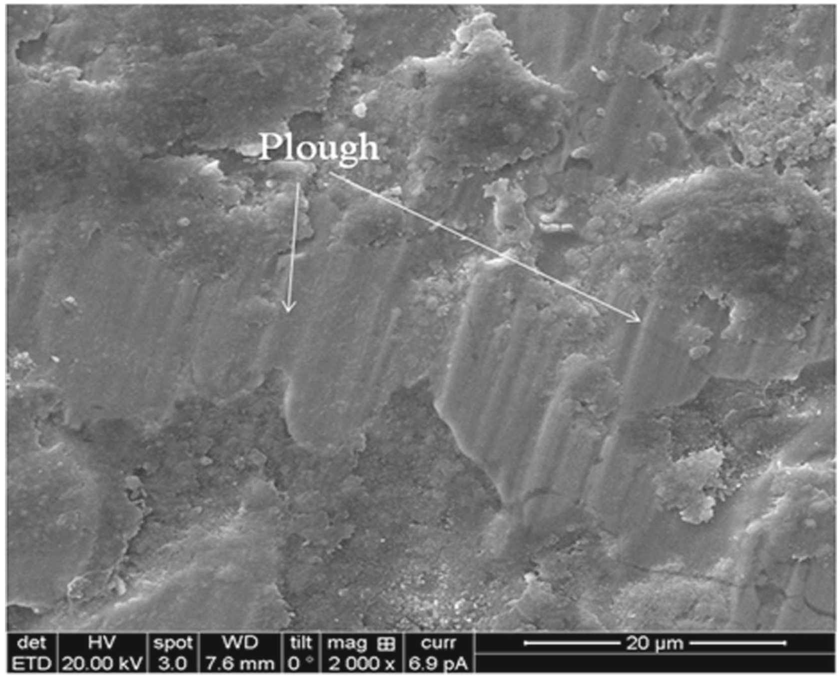


Fig. 10 Ploughing and wear tracks on the worn surface of plasma-sprayed Mo coating

3.3.3 Effect of Sliding Speed on Wear Volume Loss

Figure 15 illustrates that the wear volume loss of the laser remelted plasma-sprayed Mo coating is very much lower than the untreated plasma-sprayed Mo coating. The defects connected with the plasma-sprayed coating could be eliminated or reduced by laser remelting. The laser remelting provides a dense and pore-free microstructure. The better tribological performance of the laser remelted plasma-spray coating is basically due to the presence of a metallurgical bond between the splats.

The volume loss of the laser remelted plasma-spray coating increases as the sliding speed increases as observed in Fig. 15. The plasma-sprayed coatings usually fail along the interface of the splats. Certainly, the temperature gradient built up between the substrate the coating as the sliding

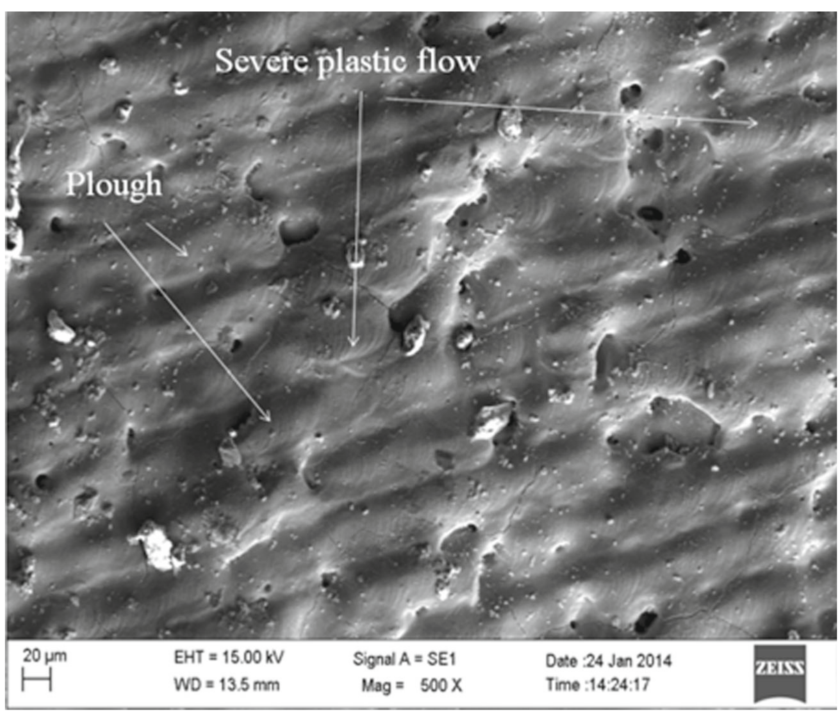


Fig. 11 Micrograph showing ploughing track

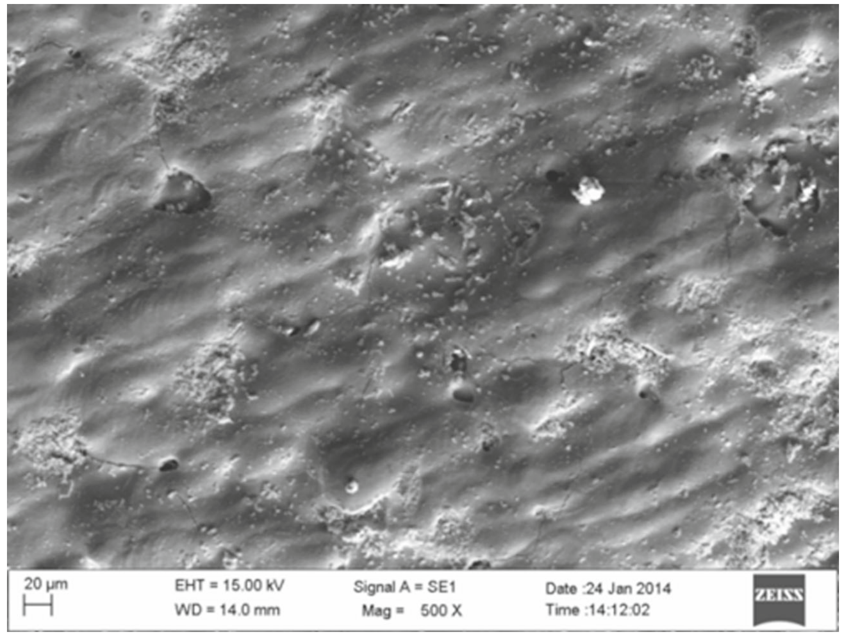


Fig. 12 Micrographs showing spallation

speed increases causes stress development. The stress development in the coating weakens the interface bond between splats and leads to failure of the coating.

Figure 16 illustrates worn surfaces of the laser remelted plasma-sprayed Mo coating tested under different speeds. Figure 16a shows fractured splats, ploughing and traces of tribo-film formation on the worn surfaces of laser remelted plasma-sprayed Mo coatings.

As the sliding speed increases the temperature at the contact zone also increases and leads to thermal softening of the coating surface. Because of this reason much more intense ploughing was observed (Fig. 16b) at higher speed. The strident thermal stress develops in the surface layer of the coating due to the high frictional heat. The thermal stress that occurs in the surface layer of the coating leads to the formation of microcracks [22]. The microcracking intensifies with increasing sliding speed. The propagation of the microcracks is responsible for the delamination of the coating. Figure 16b depicts delamination and ploughing which is responsible for the rigorous wear volume loss.

The innate defects associated with plasma-sprayed coatings such as high porosity and poor bond strength can be repaired by laser remelting. The laser remelting provides a dense and a pore-free microstructure. The results from Figs. 6, 13 and 15 demonstrate that the laser remelted Mo coating exhibits better tribological behaviour compared to the untreated Mo coatings. The improved tribological performance of laser alloyed coatings is essentially due to the presence of a metallurgical bond between the substrate as well as between splats and a significant decrease in

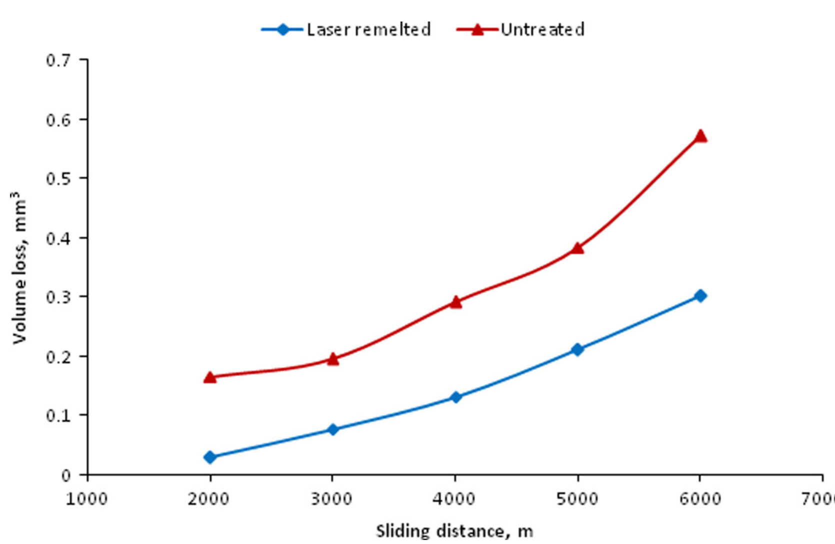


Fig. 13 Effect of sliding speed on volume loss

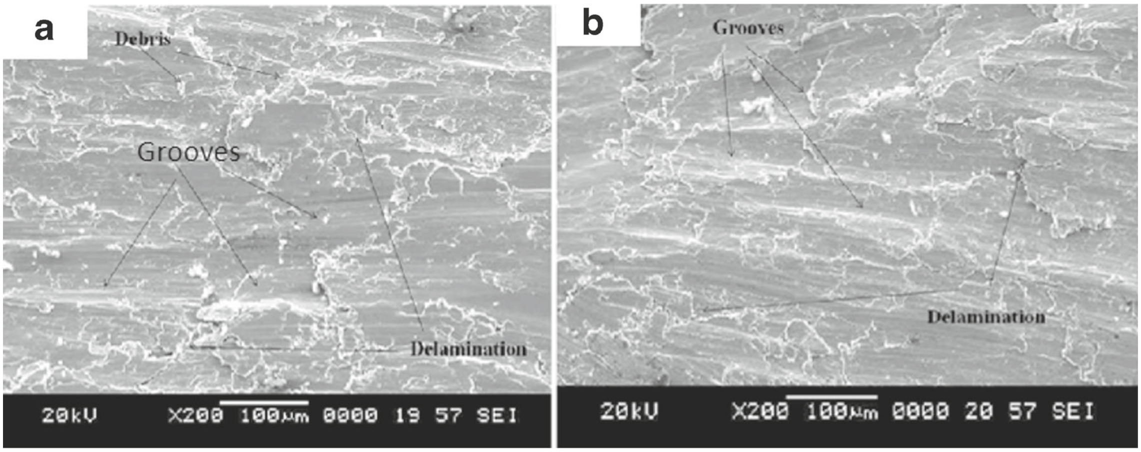


Fig. 14 Worn surface of laser remelted Mo coating at (**a**) lower sliding distance (**b**) higher distance

Fig. 15 Variation of volume loss at different sliding speed

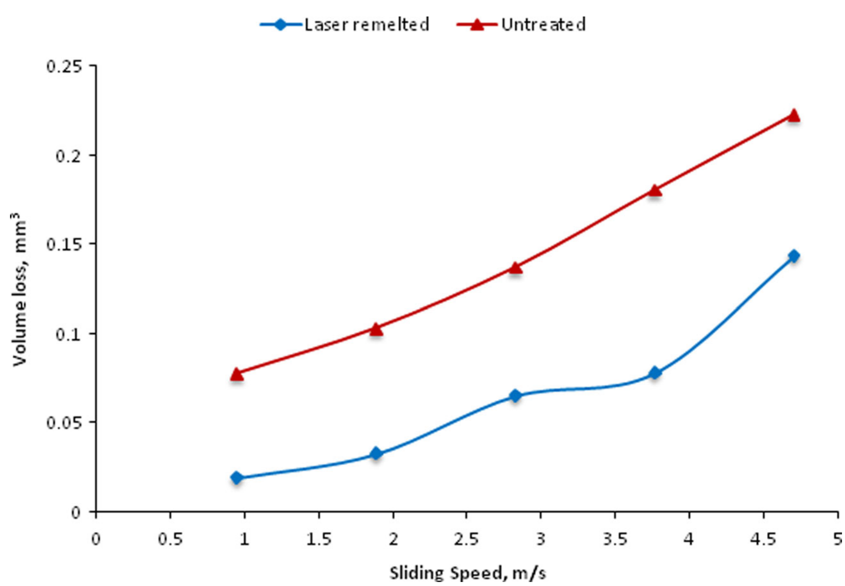
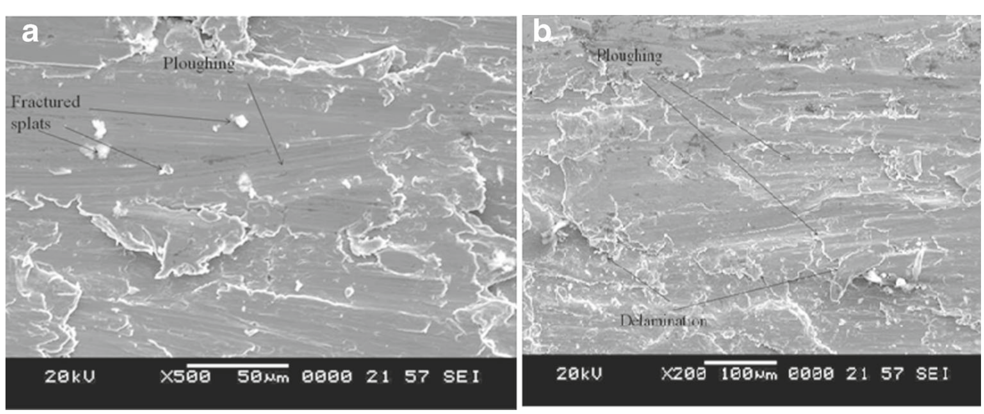


Fig. 16 Worn surface of laser remelted Mo coating at (**a**) lower sliding speed (**b**) higher speed



the porosity. The small increase in microhardness and the improvement in the surface roughness of the laser treated coatings also contribute to the enhanced wear resistance.

4 Conclusions

In the present investigation, the influence of laser melting on porosity, hardness and wear volume loss of coatings was investigated. The following conclusions are drawn from the present study:

- The degree of porosity decreased from 10.83% to 1.34%. The reduction in porosity is due to remelting of the molybdenum coating, which enhances the compaction of the structure and allows a lot of pores in the as-sprayed coating to coalesce and escape.
- The microhardness of the melted layer of the Mo coatings was enhanced. The enhancement was due to substantially reduced pores and other defects.
- The volume loss of laser remelted Mo coatings increases with increase in applied load. The main wear mechanism responsible for wear was ploughing and abrasive wear.
- The volume loss of laser remelted Mo coatings increases with increase in sliding distance and sliding speed. The wear mechanism responsible for wear was ploughing fracture of splats and delamination.
- The laser remelted Mo coating exhibits better tribological behaviour compared to the sealed and untreated Mo coatings. The improved tribological performance of laser remelted coatings was essentially due to the presence of a metallurgical bond between the splats and a significant decrease in the porosity.

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