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Laser shock peening of AISI 304 stainless steel for the application to seawater desalination pump components

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ABSTRACT

The enhancement of abrasion and corrosion resistance of AISI 304 stainless steel by laser shock peening (LSP) is reported. The optimal process conditions to achieve maximum surface hardness were determined to be laser intensity of 10 GW/cm^2, pulse density up to 25 pulse/mm^2, and 100 μm thick Al foil as the protective coating. As a result of laser shock peening, the wear volume and corrosion rate decreased by 50% and 86%, respectively, from those of unpeened material. It is considered that significant reduction in maintenance cost and extension of life time of pump components can be achieved by properly applying LSP on seawater desalination pump and pump components.

Keywords: Desalination pump; Laser shock peening; Hardness; Wear; Corrosion

1. Introduction

A multi-stage high-capacity pump is one of the essential hydraulic systems at a reverse-osmosis type seawater desalination plant. Since the high-capacity pump operates at extremely high pressure in seawater environment, the extreme operation conditions of seawater desalination pumps are likely to cause corrosion and wear of pump components, especially of the rotating parts such as ring, bush, and sleeve, resulting in the increase of maintenance and operation cost. To minimize corrosion and wear of the pump and its components, stainless steels that have high strength and corrosion resistance are typically selected as the manufacturing material of a seawater desalination pump. Despite the intrinsic high corrosion resistance and excellent mechanical properties of stainless steel, it is known that stainless steels are also subject to corrosion [1] and fatigue cracking under seawater environment. Accordingly, various techniques to enhance the surface mechanical properties and corrosion resistance of stainless steel such as plasma nitriding [2], low temperature chromizing [3], shot peening [4], laser shock peening [5] etc. have been applied for different types of stainless steel. Among these surface treatment techniques, laser shock peening (LSP) has many advantages as compared with other methods such that it can produce a compressive residual stress over a thick surface layer (> 1 mm), easy to apply for an existing structure along its surface contour by controlling the laser beam path, simple system configuration, and so forth. It has been reported that laser shock peened surfaces have a higher surface hardness [6] than untreated surfaces and exhibit a better fatigue [7], wear [8], and corrosion resistances [9]. Accordingly, LSP has been applied in many areas of industry including aerospace [10], nuclear power plant [11], turbine engine blade [12], discs and gear [13], bearing component [14] and so on.

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In LSP, an intense laser pulse irradiates a metal workpiece to generate a strong shock wave inside the medium that then produces compressive residual stress near the surface region as it propagates through the medium [15]. The induced compressive residual stress within the surface layer results in the improvement of abrasion resistance and anti-corrosion property of stainless steel. During LSP, the workpiece is immersed in water or sprayed by a water jet in order that the laser plasma can be confined and thus effectively generate a high strength shock wave propagating through the metal. Also, since the surface of a metal can be highly reflective, the metal surface is typically coated with an absorbent material to enhance the absorption of incident laser energy and thus produce a stronger shock wave. The strength of laser shock wave during LSP is closely related to the ablation conditions such as laser intensity, pulse density, and absorbent coating material [15].

In this work, experimental results for the laser shock peening of AISI 304 stainless steel are reported. Specifically, the enhancement of surface hardness with respect to process parameters such as laser intensity, number of pulse, and coating material is investigated in detail, and an optimum process condition is determined. Then, the effects of LSP on the abrasion and corrosion properties of AISI 304 stainless steel are investigated using the pin-on-disc and the potentiodynamic polarization tests, respectively. The applicability of laser shock peening for surface treatment of the mechanical parts of a seawater desalination pump is discussed.

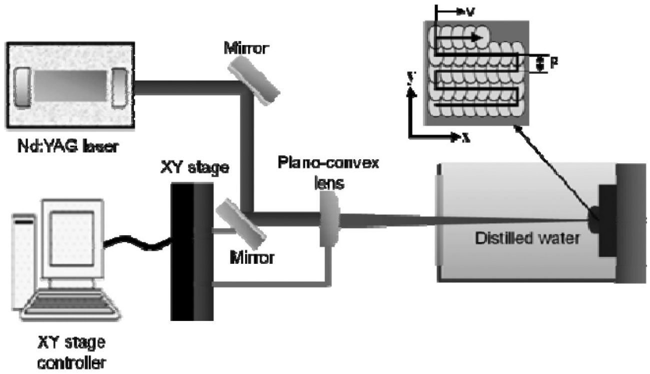

Fig. 1. Schematic diagram of the experimental setup for laser shock peening and the irradiation pattern on a sample.

2. Experiments

The schematic of experimental set up for LSP of stainless steel utilized in this study is shown in Fig. 1 in which a pulsed Nd:YAG laser (wavelength = 532 nm, pulse duration = 8 ns, pulse energy = 1.5 J) irradiates the samples immersed in water. The samples for LSP were 50 mm (width) × 50 mm (height) × 5 mm (thickness) in size and laser irradiation was carried out over a 15 mm × 15 mm area approximately in the middle by translating the sample using a X-Y motorized stage. The laser beam was focused using a plano-convex lens (focal length = 400 mm) and the laser beam spot diameter at the sample surface was adjusted within 1–2.5 mm depending on laser beam intensity. Laser pulse density (D_p), defined by $D_p = RR/(v \times p)$ where RR is the repetition rate of the laser and v and p are the scanning speed and the pitch of scan lines (see Fig. 1), respectively, was controlled by changing the translation speed of the motorized stage. A protective coating was applied on the sample surface to protect the sample surface from possible damage and also to enhance laser beam absorption. Three different types of coating material, aluminum foil (100 μm thick), iron foil (50 μm thick) and organic black paint (100 μm thick), were selected as the test materials.

The effectiveness of LSP was evaluated first by measuring the surface hardness of irradiated samples using a micro Vickers hardness tester (AKASHI, HM-112; test weight = 200 g, loading time = 5 min). For accuracy, the average values of measured hardness from the laser treated (six points with 1 mm spacing) and untreated (two points) areas were used as the representing values.

The enhancement of abrasion resistance was measured using a pin-on-disc method (Fig. 2a) [16] for which a pin-on-disc wear tester (R&B Inc, TRIBOSS Model PD-102) was utilized. The pin was made of SKD 61 with a diameter of 3 mm (Fig. 2b), whereas the sample was prepared as a disc with a diameter of 15 mm (Fig. 2c). During the measurement, a load of 3 kg was applied to the pin while the disc was rotated at a speed of 600 RPM as shown in Fig. 2a. After wear test, the profile of wear track was measured using a confocal surface profiler (Nanofocus, AG Surf) from which total wear volume can be obtained by multiplying the cross sectional area and circumference of the wear track.

For the evaluation of corrosion characteristics, potentiodynamic polarization tests were carried out for both laser peened and unpeened samples in accordance to ASTM G5 [17]. For these tests, the samples were cut into 10 mm × 10 mm size and polished by 2000-grit SiC sand paper. The corrosion tests were performed in a 3.5 wt% NaCl solution to which nitrogen gas was injected for 120 min at a rate of 200 ml/min to purge oxygen prior to the tests. For the corrosion current measurement, carbon rod and saturated calomel electrode (SCE) were used as the counter and reference electrodes, respectively, and the potential of the potentiostat (PerkinElmer Co. Model 273A) was varied within a range of –1000 to 1000 mV at a scanning rate of 0.166 mV/s. The resulting data were plotted for corrosion potential referenced to SCE (V) vs. log current density.

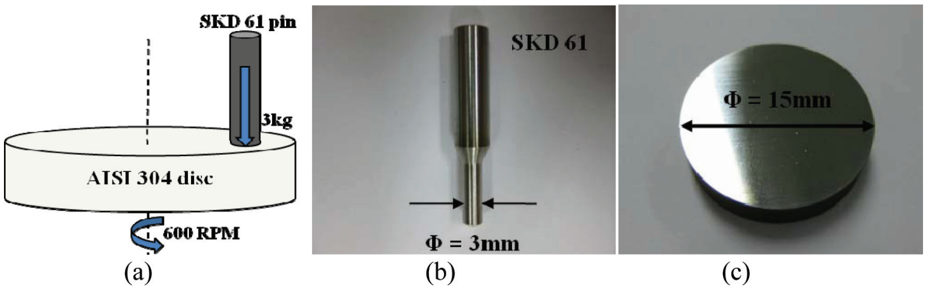

Fig. 2. (a) Schematic of the pin-on-disc method and photographs of (b) the wear pin and (c) disc.

3. Results and discussion

The effects of protective coatings on surface quality and on the enhancement of surface hardness were examined by conducting the LSP experiments on samples with different coatings as shown in Fig. 3: uncoated sample and coated samples with organic black paint (thickness = 100 μm), Fe foil (thickness = 50 μm), and Al foil (thickness = 100 μm). For LSP of these samples, laser intensity and pulse density were fixed at 10 GW/cm^2 and 25 pulse/mm^2, respectively. Fig. 4 shows the surface hardness of these samples measured after LSP with that of the unpeened sample for comparison. These data demonstrate that although LSP generally enhances the surface hardness of AISI 304 stainless steel, the effectiveness of LSP process varies significantly depending of the coating material; increase of surface hardness by 8% for uncoated sample, 16% for 100 μm organic black paint, 31% for 50 μm thick Fe foil, and 53% for 100 μm thick Al foil. A relatively thicker Al foil than the Fe foil was used due to the easy damage of 50 μm thick Al foil during experiments. Based on these results, 100 μm thick Al foil was determined as the coating material for LSP experiments in the following.

The changes of surface hardness with respect to process parameters are summarized as follow. First, Fig. 5 shows the enhancement of surface hardness of AISI 304 stainless steel by LSP with respect to laser intensity. The laser pulse density for these experiments was fixed at 25 pulse/mm^2. As shown in Fig. 5, the average hardness increased by 43% at 5 GW/cm^2, 53% at 10 GW/cm^2 and 51% at 15 GW/cm^2, implying that the optimum laser intensity for LSP of AISI 304 stainless steel is around 10 GW/cm^2. Fig. 6 shows the effects of laser pulse density on surface hardness during LSP. The laser intensity for these experiments was fixed at 10 GW/cm^2. In general, the surface hardness increased for increasing laser pulse density. However, the maximum laser pulse density in experiment was limited to 25 pulse/mm^2 due to the damage of Al foil. The use of a thicker foil may extend the limit of laser pulse density, but at the same time it will reduce the strength of laser shock delivered to the sample. Note,

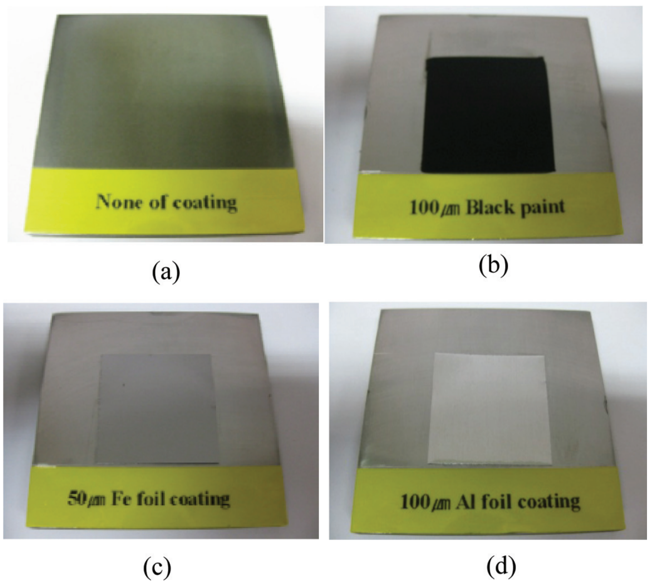

Fig. 3. Photographs of the samples for laser shock peening: (a) uncoated, (b) coated with 100 μm black paint, (c) 50 μm thick Fe foil, and (d) 100 μm thick Al foil samples.

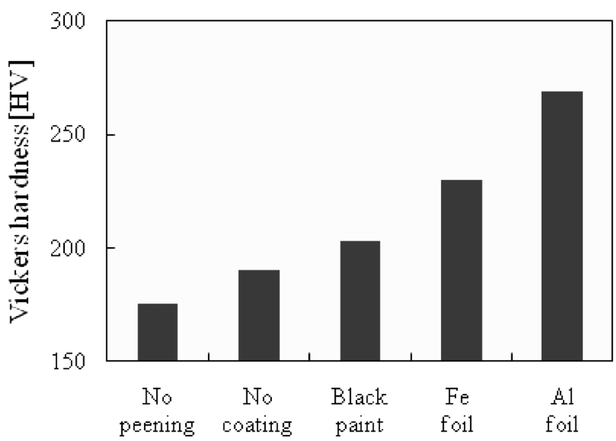

Fig. 4. Effects of the types of protective coating material on the Vickers hardness of laser shock peened AISI 304 stainless steel.

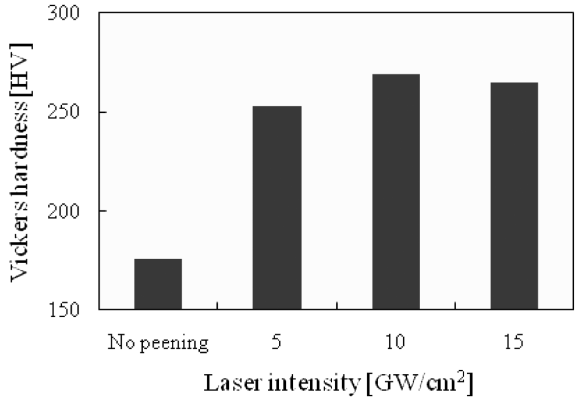

Fig. 5. Effects of laser intensity on the Vickers hardness of laser shock peened AISI 304 stainless steel.

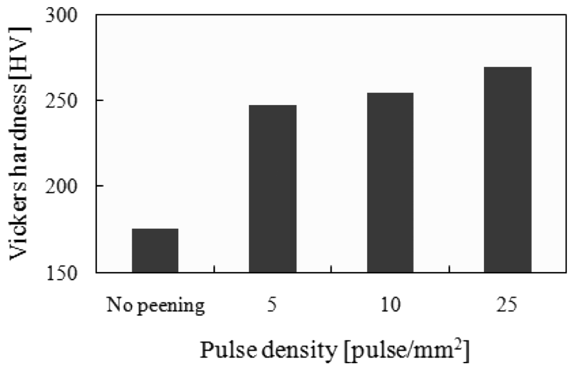

Fig. 6. Effects of pulse density on the Vickers hardness of laser shock peened AISI 304 stainless steel.

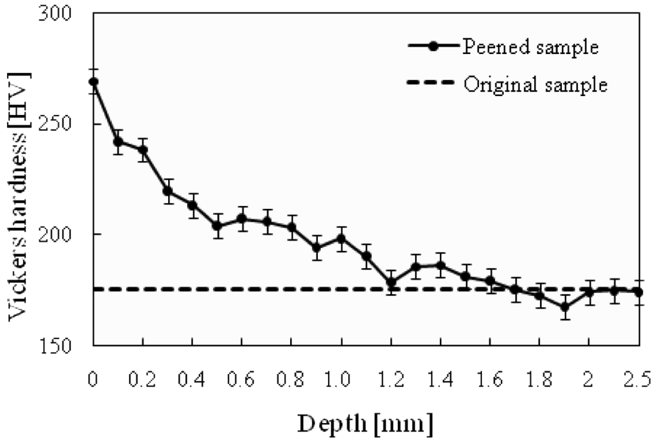

Fig. 7. Vickers hardness measured along the depth of unpeened and laser shock peened samples.

however, that no further investigation about the optimum thickness of Al foil was carried out in this study.

Based on the above results for varying process parameters, the optimal process conditions for LSP of AISI 304 stainless steel were determined as 100 μm thick Al foil for the protective coating, laser intensity of 10 GW/cm^2, and laser pulse density of 25 pulse/mm^2. Fig. 7 shows the hardness measured along the depth of laser shock peened samples from which the hardening depth of the AISI 304 is estimated to be around 1.5 mm. This hardening depth is understood to be substantially greater than that can be achieved with shot peening method. In the shot peening, the peened layer over which compressive residual stress develops is known usually not to exceed 0.25 mm in soft metals such as aluminum alloys and even less in harder metals [18]. A large hardening depth could be a significant benefit for practical application, and these data reveal that superior results can be achieved with LSP to those by shot peening method.

While the surface hardness data of the laser shock peened samples provide rather indirect information about how useful this technique is for practical applications, the wear and corrosion characteristics may directly indicate the effectiveness of LSP over untreated samples. For this purpose, the wear characteristics of laser shock peened samples were examined using the pin-on-disc method. The samples for the wear test were prepared by LSP at the conditions of laser intensity of 10 GW/cm^2 and varying pulsed density with Al protective foil. The running time during the pin-on-disc test was 120 min. The pictures of the wear test sample before and after a test are shown in Figs. 8a and 8b. By measuring the cross sectional profile of the wear track, wear volume can be obtained as shown in Fig. 8c. In general, the wear volume decreases with increasing pulse density, and these results are consistent with the hardness data in Fig. 6; the higher surface hardness, the higher abrasion resistance [8]. As compared with the wear volume of unpeended AISI 304 stainless steel (3.48 mm^3), the wear volume of laser shock peened sample at the pulse density of 25 pulse/mm^2 condition decreased by 50% (1.74 mm^3), which directly demonstrate the effectiveness of LSP on improving abrasion property of AISI 304 stainless steel.

Figs. 9a and 9b show the results of potentiodynamic polarization tests of the unpeened and peened samples, respectively; the experimental conditions were laser intensity of 10 GW/cm^2, pulse density of 25 pulse/mm^2. The corrosion current density estimated from these curves for the unpeened and peened samples were 14.2 μA/cm^2 and 1.89 μA/cm^2, respectively. Using the measured corrosion current density, the corrosion rate can be calculated by the following equation [19].

$$\text{Corrosion rate (mm/y)} = \frac{3.27 \times 10^{-3} \times i_{corr} \times \text{E.W.}}{d} \qquad (1)$$

where E.W. is the equivalent weight (g), i_{corr} is the corrosion current density (μA/cm^2), and d is the density of AISI 304 stainless steel (g/cm^3). The equivalent weight and

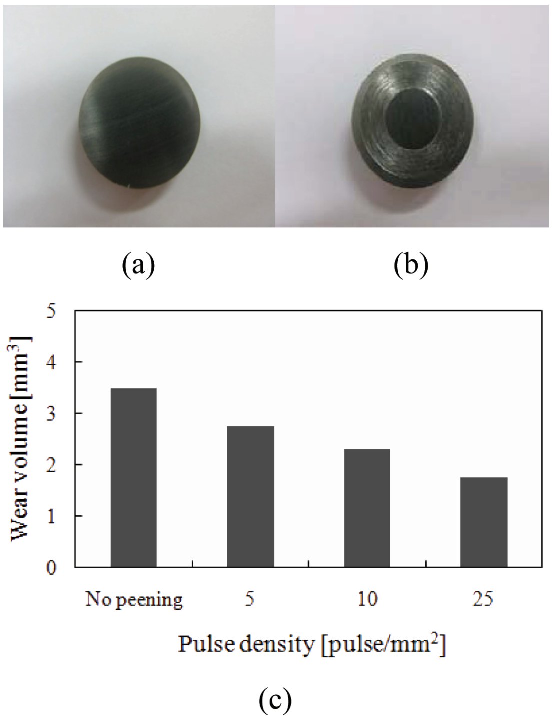

Fig. 8. Photographs of the peened AISI 304 wear disc (a) before and (b) after wear test, and (c) the effects of pulse density on the wear volume of AISI 304 stainless steel (running time = 120 min).

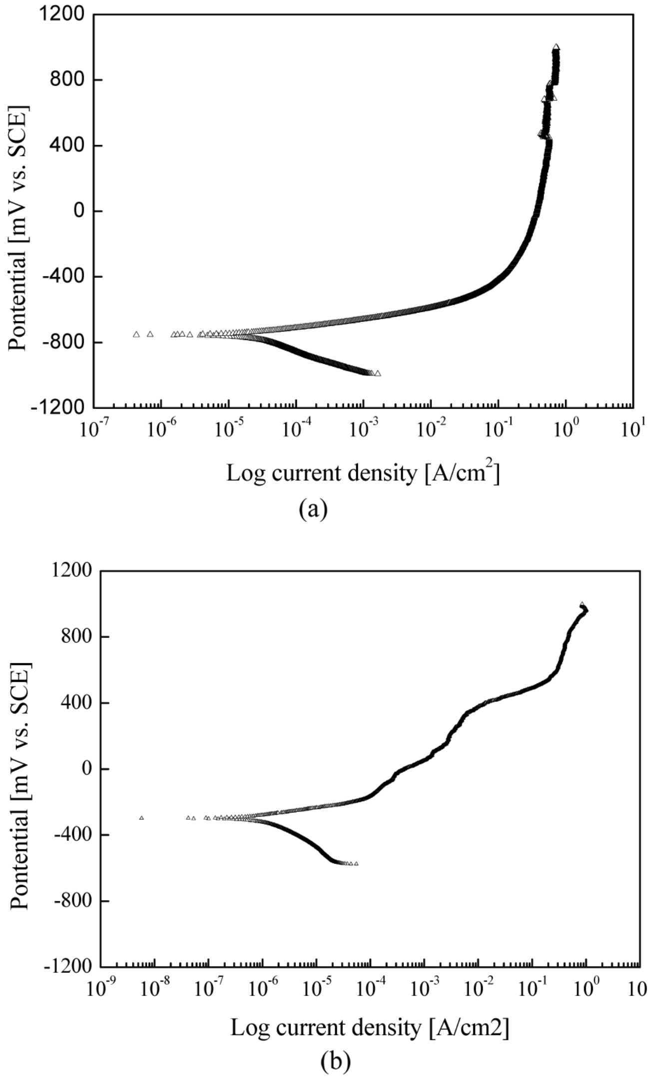

Fig. 9. Potentio-dynamic polarization curves of (a) unpeened and (b) laser shock peened AISI 304 stainless steel.

density of AISI 304 are 25.12 g [20] and 8 g/cm^3, respectively. From Eq. (1), the corrosion rate of unpeened AISI 304 is estimated to be 145.8 × 10^{-3} mm/y, whereas that of the peened sample is 19.42 × 10^{-3} mm/y, a reduction by 86%. These results again demonstrate the effectiveness of LSP in reducing corrosion of AISI 304 stainless steel components in corrosive environments.

The cross-sectional micrographs of unpeened and peened (10 GW/cm^2, 25 pulse/mm^2, Al protective coating) AISI 304 stainless steel samples are shown in Figs. 10a and 10b, respectively. For clearer imaging, the samples were electrically polished at 1.5 V in 30% nitric acid. If thermal effect becomes pronounced, microstructural changes such as deformation induced martensite [21] or recrystallization [22] can take place in AISI 304 stainless steel. However, no indication of deformation induced martensite is observed in Fig. 10(b), which is consistent with the results by Nikitin et al. [23]. The average grain sizes of the unpeened and peened samples in Figs. 10(a) and 10(b), counting only the large grains, are about 50 and 48 μm, respectively. This little variation of grain size is understood to be implying negligible microstructural changes before and after the LSP process.

4. Conclusion

From LSP experiments of AISI 304 stainless steel, it is demonstrated that the surface hardness of this material can be increased by maximum 53% if the process parameters are selected appropriately. By applying the LSP at optimal conditions, the wear volume and corrosion rate of AISI 304 stainless steel could be reduced by 50% and 86.7%, respectively, from those of unpeened material. The observed enhancement of abrasion and corrosion properties of AISI 304 stainless steel by LSP is understood that the application of LSP for high capacity pump components is a practical option to extend the life time of pump parts and reduce operation cost.

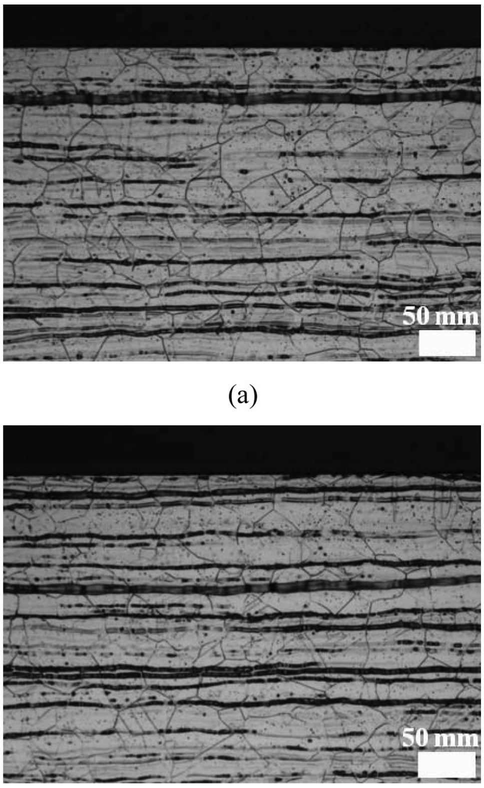

Fig. 10. Cross-sectional SEM images of the microstructures of (a) unpeened and (b) laser shock peened AISI 304 stainless steel.

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