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The effects of the confining medium and protective layer during femtosecond laser shock peening

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A B S T R A C T

Nanosecond laser shock peening is an important material strengthening technique, but its application is limited by the requirement of the confining medium and protective coating. These limitations can be potentially overcome by femtosecond laser shock peening. This article presents a study on the effects of the confining medium and protective coating on femtosecond laser shock peening of 304 stainless steel. The surface hardness can be increased by 45.5% by peening directly in air without any confining medium and coating. The surface quality is also maintained at a good condition. Numerical simulation by a hydrodynamic model reveals that femtosecond laser shock peening can induce extremely strong shock waves (hundreds of GPa) directly in air, which is much stronger than those by nanosecond laser peening (~10 GPa). Surprisingly different from nanosecond laser peening, it is found that by adding the confining medium and protective layer, the peening effect is significantly weakened. It is unveiled that the super high intensity of the femtosecond laser causes strong ionization of the confining medium (water), which shields 98% of the laser energy from deposition into the sample and weakens the peening effect. The enhancement depth by femtosecond laser peening is found to be less than 100 mm, which is the reason that the peening effect is weakened when a 100 mm thick coating is used. This study shows that femtosecond laser peening works the best directly in air without any confining medium and coating, which significantly broadens its application where high flexibility and precision are required.

1. Introduction

Laser shock peening (LSP) is a surface engineering process that imparts beneficial residual stresses in materials and improves material properties such as surface hardness, fatigue life and corrosion resistance [1–4]. When a high intensity laser beam strikes a sample surface, a strong shock wave is generated into the sample by the expansion of laser-induced plasma near the surface. The current laser shock peening technology typically uses a nanosecond laser, which is commercially used in automotive, aerospace, nuclear and medical areas. However, nanosecond laser shock peening (ns-LSP) requires a confining medium (e.g. water or glass) and a protective coating, due to the insufficient shock wave intensity and severe surface thermal damage, respectively [5–10]. These additional procedures bring extra cost and difficulties in dealing with complex geometry.

Femtosecond laser shock peening (fs-LSP) provides an alternate to overcome the barriers inherent in ns-LSP, since it can generate stronger shock wave due to the ultra-high laser intensity, while reducing the thermal damage thanks to the small heat-affected zone [11]. Moreover, because of the ultra-short laser pulse duration, the reduced plasma shielding effect improves the energy deposition efficiency. There are only a few previous papers studying this topic. It was first demonstrated by Nakano et al [3,12] in water without a protective coating. The surface hardness improvement by fs-LSP was found similar to the results by ns-LSP, and the authors proposed that the fs-LSP had the potential to improve the surface hardness of metals under extremely low laser energy. Sano et al. [13] and Wang et al. [14] studied the effects of fs-LSP without confining medium and sacrificial overlay on the fatigue life of 2024 aluminum and corrosion resistance of NiTi alloy, respectively. Hoppius et al. [15] reported the effect of the sacrificial layer on the surface morphology after fs-LSP and the resultant peening results.

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Majumdar et al. [16] investigated the residual stress and microhardness of medium carbon steel after fs-LSP in air and in water.

Although fs-LSP has been shown working without a confining medium and protective coating, the fundamental mechanism is not well understood. Additionally, it is not clear how the confining medium and the coating affect the peening results and what is the optimal processing condition. This study aims to study the influence of processing conditions (air/water, with/without coating) and laser parameters on femtosecond laser peening.

2. Experiments and methods

The experimental setup is shown in Fig. 1. A Yb:KGW femtosecond laser source (Pharos by Light Conversion) was employed to deliver laser pulses at a wavelength of 1030 nm, duration of 165 fs (full width at half maximum), repetition rate 6 kHz (kHz), and pulse energy up to 1 mJ. The laser beam was delivered through a laser scan head (intelli*SCAN* by Scanlab) and a F-Theta objective lens to scan on the sample surface. The surface focal spot size was 34 μm. 304 stainless steel samples with dimensions of 2.8 cm × 1.4 cm × 0.45 cm were used in this study. Before the experiment, the samples were fully annealed at 1100 °C for 30 mins in vacuum, followed by water quenching. The experiment surface was ground with SiC sandpapers up to 1200 grit and polished with 3 μm diamond suspension to obtain a mirror-like and stress-free surface. A container was used to hold the sample, which could be exposed to air or submersed in water. When testing the effect of the protective layer, a 100 μm aluminum foil was used to cover the sample surface. The peak laser fluence was varied from 30 to 60 J/cm². The overlapping ratio, denoted by g, is to describe and control the distribution of laser pulses on the impact surface, which is expresses as:

$$g = \frac{\mathrm{D}}{D} \times 100\% \qquad (1)$$

where D is the spot diameter, D is the coincidence length of two successive laser spots.

After fs-LSP, surface and in-depth Vickers microhardness were measured using a Wilson Micro Hardness Tester (Tukon 1202). A Vickers indenter was used with 25 gf load and 10 s dwell time. For surface hardness measurement, 3 repeated samples were measured from 5 random positions on each sample. The in-depth hardness was carried out on cross-section of sample cut by a low-speed precision diamond saw. To analyze the surface roughness and ablation depth with femtosecond laser, a 3D-profilometer Olympus LEXT OLS4000 was used. The measured area was selected from the central region on which the instrument measured four regions and calculated the average roughness Sa. Sample surface roughness before fs-LSP was 0.04 μm. Prior to fs-LSP, the surface hardness was 246 ± 11 HV. Table 1 summarizes the processing conditions for 304 stainless steel sample. The laser beam with fluences 30, 40 and 60 J/cm² of 50% overlapping ratio was introduced to the sample submersed in water or exposed to air. Additionally, the effect of overlapping ratio was tested with 20%, 30%, 50% and 80% overlapping ratio of 40 J/cm² without the aluminium foil coating.

3. Results and discussions

Fig. 2(a) summaries the surface hardness results at different processing conditions and laser fluences. The overlapping ratio was maintained at 50% for all tests. Prior to fs-LSP, the surface hardness was 246 ± 11 HV. It shows that the treatment in air condition without the aluminum foil coating gives the greatest surface hardness enhancement, up to 328 HV, which is 33.3% higher than the untreated material hardness. This result is similar, if not better than ns-LSP with the confining medium and the protective layer. The effect of increasing overlapping ratio on surface hardness is shown in Fig. 2(b). When the overlapping ratio increases gradually, the surface hardness increases accordingly. The highest hardness is achieved at 80% overlapping ratio, and this maximum hardness enhancement is up to 358 HV, which is 45.5% higher than the base material surface hardness. To understand why fs-LSP gives rise to superior enhancement result without the assistance of the confining medium, a hydrodynamic model was employed to simulate the femtosecond laser single-pulse ablation of stainless steel [17]. Fig. 3(a) shows the laser-induced shock wave propagation in the sample with a laser fluence of 40 J/cm². When propagating into the sample, the generated shock can reach as strong as several hundred GPa at the depth of several hundred nanometres. It should be noted that the ultra-high pressure near the original sample surface does not induce any peening, since a 130 nm layer of the material will be removed from the bulk after laser ablation. The actual pressure applied to the remaining surface will be at the level of several hundred GPa. This ultra-high pressure by fs-LSP is at least one magnitude higher than the pressure by ns-LSP [5–8], which could efficiently compress the material. Therefore, fs-LSP does not need the confining medium to further strengthen the shock wave and can be performed directly in air. Moreover, in air without coating, fs-LSP exhibits decreasing of surface hardness when the laser fluence increases from 40 J/cm² to 60 J/cm². This could be possibly induced by the surface tensile stress or the ionization of air. The analysis of this phenomenon will be carried on in a future study.

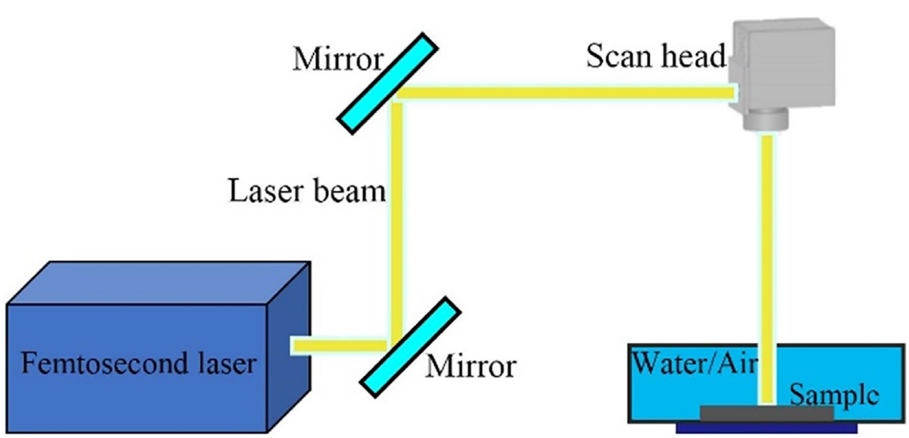

Fig. 1. Schematic illustration of the experimental setup.

Table 1
The processing conditions for 304 stainless steel.

Fluence conditions	30 J/cm^2	40 J/cm^2	60 J/cm^2
In air no coating	50%	20%, 30%, 50%, 80%	50%
In air with coating	50%	50%	50%
In water no coating	50%	50%	50%
In water with coating	50%	50%	50%

As shown in Fig. 2(a), by adding the aluminum foil as the protective coating, the surface hardness is only slightly increased after fs-LSP, and the enhancement is much smaller than fs-LSP without the coating. The reason is that the shock wave penetration depth by fs-LSP is less than the thickness of coating (100 mm).

Fig. 3(b) demonstrates the in-depth hardness distribution of the sample processed in air without coating. The laser fluence was 40 J/cm^2 and the overlapping ratio was 50%. Based on the measurement, it shows that the hardness enhancement is the highest on the surface and gradually decreases when going deeper into the sample. The thickness of the layer with improved hardness is around 60 mm, which indicates the penetration depth of the laser-induced shock wave. According to this result, when adding an aluminum coating on the sample surface, the laser-induced shock wave will be only absorbed by the aluminum coating and cannot penetrate into the stainless steel sample, which is why the hardness of the sample was not increased, as shown in Fig. 2 (a). Therefore, adding a protective coating will significantly weaken the effect of fs-LSP, unless the coating is much thinner than the penetration depth of the shock wave, which is less than 100 mm. As a comparison, the shock wave penetration depth by nanosecond laser peening is a couple of millimeters, which allows the application of protective coatings with a thickness of hundreds of micrometers.

When evaluating the results of fs-LSP in water, it is surprising to see that fs-LSP in water did not induce any improvement to surface hardness at any laser fluence, with or without coating. This finding is contradictory to our experience with ns-LSP, where a confining medium is required to suppress the expansion of the plasma, increase the shock wave intensity, and improve the peening effect. To understand the mechanism of this interesting phenomenon, the calculated surface pressure evolutions during fs-LSP in air and in water at the same laser fluence are shown in Fig. 4(a). At 20 J/cm^2, the peak surface pressure by ablation in air is 417 GPa, while it is only 36 GPa when water was use as confinement media. When the laser fluence is increased to 40 J/cm^2, the peak pressure in air is increased to 505 GPa, while the pressure in water does not change much. This is due to the strong water ionization. Compared with fs-LSP in water, even though air has lower ionization potential, the density of air is much smaller than the density of water, the ionization of which could generate the free electrons up to the order of 10^{29} atoms/m^3, which is similar to the free electron density of metal. Hence, the shielding effect is stronger in water. According to the simulation, at the laser fluence of 40 J/cm^2, water absorbs 98% of the total laser energy and only 2% can be deposited into

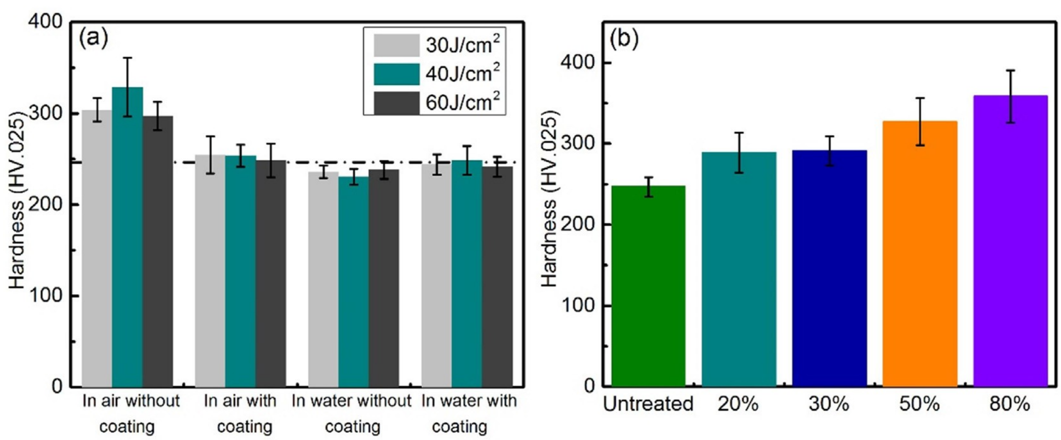

Fig. 2. (a) Surface hardness measurements under different processing conditions with laser fluence 30, 40 and 60 J/cm^2, the dash dot line represents the surface hardness of untreated material and (b) Surface hardness measurements for 20%, 30%, 50% and 80% overlapping ratio. The sample was treated with 40 J/cm^2 in air without coating.

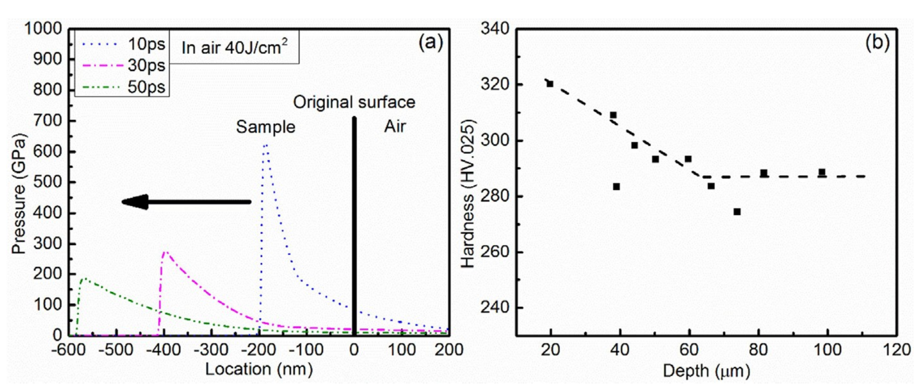

Fig. 3. (a) From simulation, the surface pressure propagation is shown for laser fluence 40 J/cm^2 in the air, the negative coordinate represents the bulk and 0 nm is the initial material surface location. and (b) the Hardness measurement along the depth for 304 stainless steel sample treated with 40 J/cm^2 without coating exposed to air.

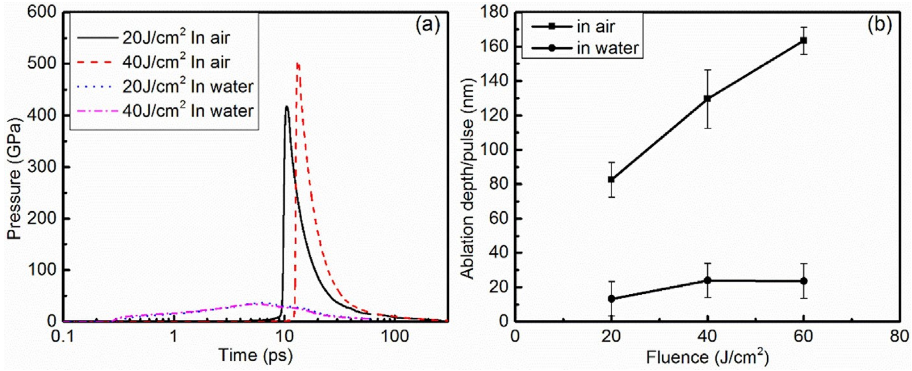

Fig. 4. (a) From simulation, the surface pressure histories are shown for laser fluences 20 J/cm² and 40 J/cm² in the air and water and (b) from experiments, the ablation depth per pulse with laser fluences 20 J/cm², 40 J/cm² and 60 J/cm² of ten pulses was measured with Olympus LEXT OLS4000.

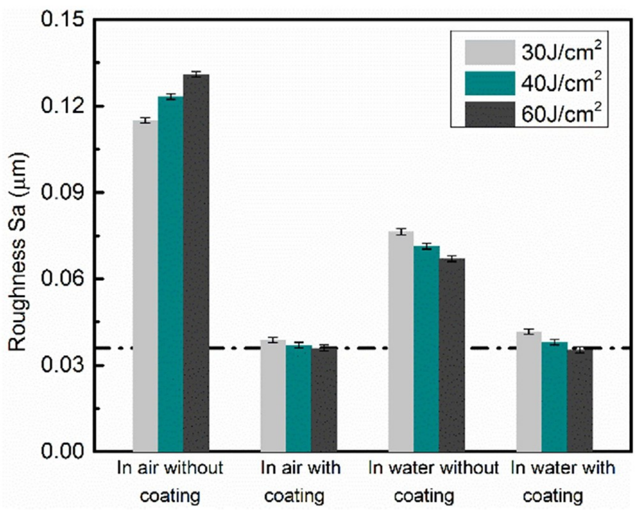

Fig. 5. Surface roughness measurements for samples under different processing conditions. The samples were treated at the laser fluences of 30 J/cm², 40 J/cm² and 60 J/cm², with/without coating, and in air/water. The overlapping ratio for all tests was 50%. The dash dot line represents the roughness of untreated material.

the sample. At the same fluence, air only absorbs 18.3% of the total laser energy, and most of the energy can be used for ablation and peening. To validate this simulation analysis, the experiment is done to measure the ablation depth in air and in water at different laser fluences, as shown in Fig. 4(b). For example, with laser fluence 40 J/cm², the testing shows that in air, the ablation depth is 130 nm/pulse, and in water, the ablation depth is 24 nm/pulse, which supports the simulation result.

Fig. 5 shows the surface roughness measurements after fs-LSP with different processing conditions. Sample surface roughness (Sa) before being processed was 0.04 lm. Although the surface quality could be slightly deteriorated (increased to over 0.13 mm) after fs-LSP in air without coating, it is much better than the surface roughness by ns-LSP (2 mm with around 50% overlapping ratio) [18]. And the surface quality with fs-LSP is at an acceptable level for many applications [19,20]. It was reported [15] that the surface morphology after fs-LSP, such as the formation of laser-induced periodic surface structures, nanoparticles adhesion, and surface oxidation, could potentially affect the peening results. These impacts are beyond the scope of this work and will be discussed in the future studies.

4. Conclusion

In this work, fs-LSP of 304 stainless steel and the effect of the confining medium and protective coating have been studied. fs-LSP has been shown to be very effective to enhance the surface hardness by 45.5% without any confining medium and protective coating, due to its extremely high laser-induced shock wave. By adding water as the confining medium, the peening effect is weakened, because of the strong water ionization and shielding of the incident laser energy. This is quite different from ns-LSP. Because of the small enhancement depth by fs-LSP, a protective coating can significantly attenuate the shock wave intensity before arriving on the sample surface, and thus weaken the peening effect. The surface quality after fs-LSP in air without coating is slightly deteriorated compared with the untreated surface, but the quality could be acceptable for many applications. This study reveals that the fs-LSP works the best in air without any coating, and could potentially open new application possibilities for peening technology.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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