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Plasma Confinement Layer via Laser Peening on a Solid-State Medium with High Acoustic Impedance

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In laser peening, a high amplitude shock impulse is necessary. The shock impulse can be increased by confinement of the laser-produced plasma through the acoustic impedance of a plasma confinement layer. In this study, a solid-state medium having high acoustic impedance was used as the plasma confinement layer for laser peening. It was found that elimination of the acoustic impedance mismatch is important for efficient laser peening. By injecting silicone oil into the gap between the solid-state medium and the target sample, the influence of impedance mismatch was reduced and efficient laser peening was achieved. Greater values of hardness and compressive residual stress were obtained in comparison with water used as the plasma confinement layer.

Keywords: laser peening, plasma confinement layer, acoustic impedance, shock wave pressure, laser ablation

1. Introduction

Laser peening is a shock processing technique used to achieve improved mechanical performance, e.g., resistance to crack initiation, fatigue life, and fatigue strength [1, 2]. These effects are obtained by a laser-induced shock wave. Laser peening provides a deeper compressive stress layer and a smoother metal surface for metals compared with con- ventional shot peening [3]. In laser peening, when a short- pulse laser irradiates the metal at intensities exceeding 10^9 W/cm^2 in a plasma confinement layer such as water, ignition and explosive expansion of the laser-produced plasma occur and generate a high shock pressure. The plasma confinement layer prevents the laser-produced plasma from rapidly ex- panding away from the metal surface. Therefore, a pressure pulse with high amplitude and short duration is generated, and the shock wave intensity is increased. Plastic defor- mation is produced in the target metal by the shock wave, and generates work hardened and residual compressive stress layers near the metal surface.

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The effect of laser peening E_{LP}, i.e., the depth of the plas- tically deformed region of the target metal, is defined in terms of two factors, the shock loading time and the shock wave pressure. That is,

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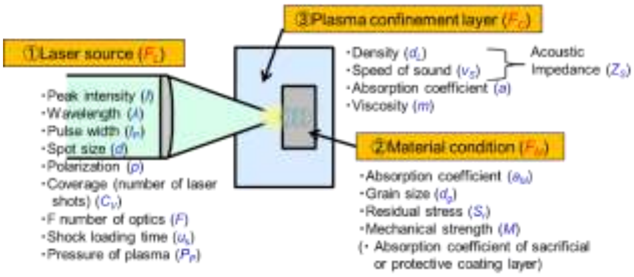


goal is to examine the optimal parameters needed for an ef- ficient laser peening treatment. For this purpose, three fac- tors associated with laser peening are shown in Fig. 1: (1) F_L, which is related to the laser source, (2) F_M, which is associ- ated with the material condition, and (3) F_C, which is related to the plasma confinement layer, have been defined [7-9]. The efficiency of the technique of laser peening can be in- fluenced by controlling these three factors.

The present study aims to control F_C, i.e., the plasma confinement layer. The plasma confinement layer sup- presses the expansion of the laser-produced plasma and con- tributes to the increase of the shock wave amplitude. The pressure of the plasma is expressed as

$$P \propto \sqrt{\frac{\alpha}{2\alpha+3} \cdot Z \cdot I} \quad (2)$$

where P is the pressure of the plasma created by intense laser irradiation, α is the interaction efficiency, I is the intensity of the laser and Z is the acoustic impedance of the plasma confinement layer [10]. As shown by Eq. (2), the acoustic

$$E_{LP} \propto \int^{\tau_s} P(t)\, dt \quad (1)$$

where τ_s is the shock loading time and P is the pressure of the shock wave induced by intense laser irradiation.

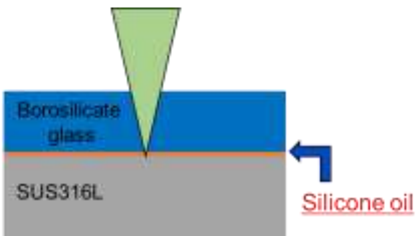
Equa- tion (1) indicates that the mechanical impulse on the target materials must be sufficiently high to realize efficient laser peening [2]. Although the efficiency of the laser peening technique needs to be improved through systematic studies taking into account many parameters, current studies on la- ser peening mainly focus on the magnitude of the compres- sive residual stress and the hardness of the metal surface ob- tained as a result of the laser peening treatment [4-6]. Our

impedance is one of the factors determining the pressure of the plasma. The acoustic impedance is analytically defined in terms of the product of two factors that depend on the den- sity of the plasma confinement layer and the sound velocity in the plasma confinement layer [10, 11]. The plasma con- finement capability is determined by the acoustic impedance. Therefore, control of the plasma confinement layer influ- ences the efficiency of the laser peening treatment.

Most previous studies on laser peening have employed water as the plasma confinement layer. The variations in plasma confinement capability due to changes in the me- dium used for the plasma confinement layer and its effects on laser peening have remained unclear. A medium with an acoustic impedance higher than that of water must be se- lected for efficient laser peening. Therefore, solid-state me- dia having higher acoustic impedance than liquid materials are more effective as plasma confinement layers. Moreover, it is possible to prevent the oxidation of the metal surface by using a solid-state medium. It was shown that glass has bet- ter confinement properties than water or air in numerical simulations of laser peening [12]. In addition, previous work on laser peening with borosilicate glass as the plasma con- finement layer has been reported [13, 14]. From these stud- ies, it was found that the effects of laser peening with boro- silicate glass were almost same as those with water. How- ever, they did not consider the efficiency of shock loading from the viewpoint of acoustic impedance matching.

Our previous studies have shown how laser peening can be controlled by the acoustic impedance of a liquid medium used as the plasma confinement layer [15, 16]. It was found that the efficiency of laser peening can be improved by con- trolling the acoustic impedance of the plasma confinement layer. A solid-state medium having high acoustic impedance should be superior as the plasma confinement layer. The acoustic impedances of air, water, SUS316L stainless steel as the target sample, and borosilicate glass are 0.000×10^{6}, 1.5×10^{6}, 44.8×10^{6}, and 11.4×10^{6} Pa · s/m, re- spectively. Suitable conditions for laser peening have not been examined from the perspective of the acoustic imped- ance of the plasma confinement layer.

In this study, a solid-state medium was used as the plasma confinement layer for laser peening. We selected



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bo- rosilicate glass as the solid-state medium, as in previous re- ports [13, 14], for the following reasons. Firstly, a borosili- cate glass medium has eight times higher acoustic imped- ance than water [17]. Secondly, this glass has excellent heat resistance. Finally, it is inexpensive and readily available. For efficient laser peening with a solid-state plasma confine- ment layer (hereinafter referred to as an SSPCL), the mis- match in acoustic impedance between the SSPCL and the

Fig. 2 To improve the impedance mismatch, silicone oil was used to reduce the acoustic impedance mismatch between thesample and the glass.

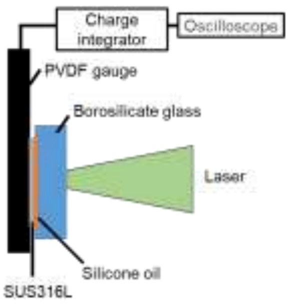

Fig. 3 Experimental setup for measurement of laser-inducedshock wave pressure by PVDF gauge.

target metal should be minimized. The shock loading does not propagate efficiently into the target metal because an acoustic impedance mismatch exists without exception due to the air gap between the SSPCL and the target metal. In this study, to improve the impedance mismatch, an imped- ance matching fluid was used. The effect of laser peening with SSPCL was investigated based on measurements of the hardness and residual stress, to achieve efficient laser peen-ing.

2. Measurement of laser-induced shock wave pressure

As explained above, a solid-state medium having high acoustic impedance should be effective as the plasma con- finement layer for laser peening. However, because of the surface roughness of the solid-state medium, the contact be- tween the SSPCL and the surface of the target sample is im-perfect. The capability of plasma confinement would be im-paired by an air gap existing between the solid-state medium and the target sample [14]. In other words, problems caused by acoustic impedance mismatch should be solved for laser peening with an SSPCL. To reduce the impedance mismatch, the air gap between the SSPCL and the target sample was filled with a medium that has higher acoustic impedance than air, silicone oil, as shown in Fig. 2. Silicone oil (KF-96- 100CS made by Shin-Etsu Silicone) has two hundred and fifty times higher acoustic impedance than air. The specifi- cations of the silicone oil are as follows: The boiling point is 150 °C, the viscosity is 100 mm^2/s and the refractive index is 1.403 at a temperature of 25 °C. Silicone oil is not chem- ically reactive with metal and has excellent heat resistance.

In order to confirm the efficacy of SSPCL, the pressure of the laser-induced shock wave was measured by a polyvi- nylidene fluoride (PVDF) gauge in a preliminary experiment for laser peening, as illustrated in Fig. 3. Second harmonic radiation from a Nd:YAG laser oscillated at a wavelength of 532 nm was used. The shock wave pressure was produced by irradiation with the single-shot laser. The pulse width and focal spot diameter were fixed at 4 ns and 200 µm, respec- tively. The laser intensity was varied from 1 to 5 GW/cm^2. SUS316L austenitic stainless steel with a thickness of 50 µm was used in the test samples. Borosilicate glass (SSPCL)

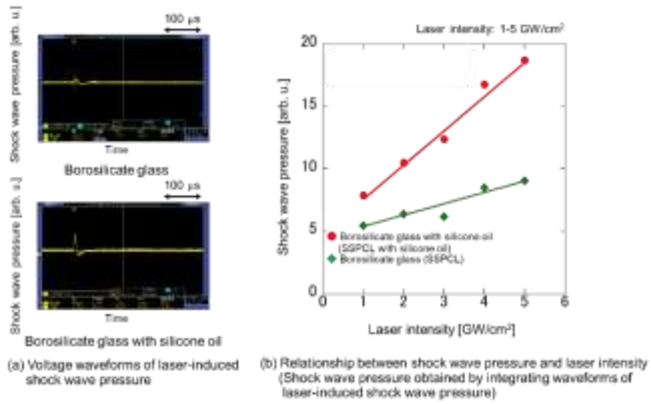

Fig. 4 Laser-induced shock wave pressure measured byPVDF gauge.

alone, and borosilicate glass with silicone oil were used. Sil- icone oil was poured on the sample surface and pressed firmly with the borosilicate glass.

Figure 4(a) shows example waveforms of the laser-in- duced shock wave pressure measured by the PVDF gauge. The vertical axis is the shock wave pressure amplitude and the horizontal axis is time. The shock wave pressure gener- ated in the SSPCL with silicone oil is larger than that gener-ated with the SSPCL alone, which indicates that the imped- ance mismatch was reduced in the case of the SSPCL with silicone oil. The impedance mismatch should be improved to obtain high pressure in the shock wave. In Fig. 4(b), the shock wave pressures found by integration of the waveform according to Eq. (1) are plotted. The vertical axis is shock wave pressure and the horizontal axis is laser intensity. The shock wave pressure increased remarkably with increasing laser intensity when the SSPCL with silicone oil was used. When using the SSPCL, the elimination of impedance mis- match is required.

3. Laser peening experiments

The experimental setup used for laser peening is shown in Fig. 5. As mentioned in the second section, the second harmonic radiation (wavelength 532 nm) of a Nd:YAG (na- nosecond) laser system that delivered a pulse energy of 200 mJ was used for all experiments. The pulse width and repe- tition rate were fixed at 4 ns

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Volume 17 Issue 1Jan 2021

and 10 Hz, respectively. The laser beam was normally incident on the sample, and was focused on the sample by a lens with a focal length of 10 cm. The laser focal spot diameter was adjusted to 200 μm. The focused beam diameter was determined by the size of the pin-hole in the optical system. The image of the pin-hole is transferred to the surface of target sample with reduced mag- nification. SUS316L stainless steel coupons having dimen- sions of 25 × 25 × 5 mm were used as test samples in all experiments. The initial properties of the target sample have an influence on the effects of laser peening, since the plastic deformation produced by any external stress is strongly af- fected by the residual stress, grain size, and number of dis- locations in a material. Samples were annealed in vacuum by heating at 900 °C for 3 h before laser irradiation to stand- ardize the initial properties of the materials. The laser peen- ing method without a protective coating, which can be used as a way to treat metals, was selected [18, 19]. Borosilicate glass was adopted as the SSPCL material. The thickness of

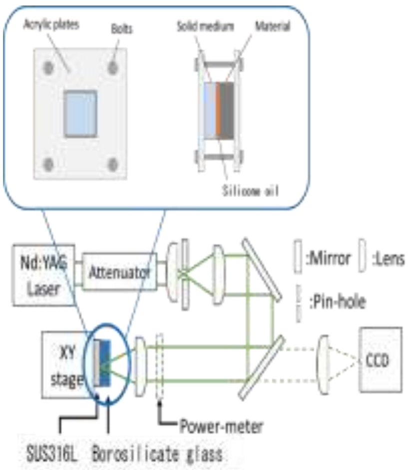

Fig. 5. Silicone oil was poured on the sample surface and pressed firmly with the borosilicate glass

the borosilicate glass was 5 mm. Water, borosilicate glass and borosilicate glass with silicone oil were used in the ex- periments. The sample was supported by a holder and im- mersed in distilled water when water was used as the plasma confinement layer. The thickness of the water layer above the sample was 20 mm. When borosilicate glass was used as the plasma confinement layer, the sample and glass were held by two acrylic plates and pressed together with screws as illustrated in. The gap between the sample and glass due to surface roughness would be several micrometers.

The laser intensity, which varied from 1 to 5 GW/cm^2, was adjusted with an energy attenuator consisting of a half- wave plate and cross polarizers. The laser intensity can be controlled easily without changing any other laser properties by rotating the half-wave plate. The coverage, which corre- sponds to the number of laser shots irradiating a unit area, was controlled by an XY stage connected to a computer, and was fixed at 500%. In the present study, the magnitude of the compressive residual stress and the surface hardening were measured to determine the effects of laser peening, i.e., to assess the laser peening performance, because residual stress and work hardening are caused as a result of plastic defor- mation. Vickers hardness and X-ray diffraction measure- ments were performed to determine the work hardening and residual stress, respectively.

4. Results and discussion

Figure 6 shows the surface hardness of the laser-peened samples as a function of laser intensity. The hardness differ- ence is the Vickers hardness minus the initial hardness. The three solid lines represent the results of laser peening when water, the SSPCL alone, and the SSPCL with silicone oil were used as the plasma confinement layer. As shown in Fig. 6, the hardness obtained with the SSPCL was almost the same as that with water, regardless of the higher acoustic im- pedance of the solid-state medium. This is presumed to be caused by the influence of the impedance mismatch due to the air gap between the sample and the glass. On the other hand, the hardness increased remarkably for the SSPCL with silicone oil. The pressure increase shown in Fig. 4(b) reflects the hardness characteristics. For efficient laser peening, the

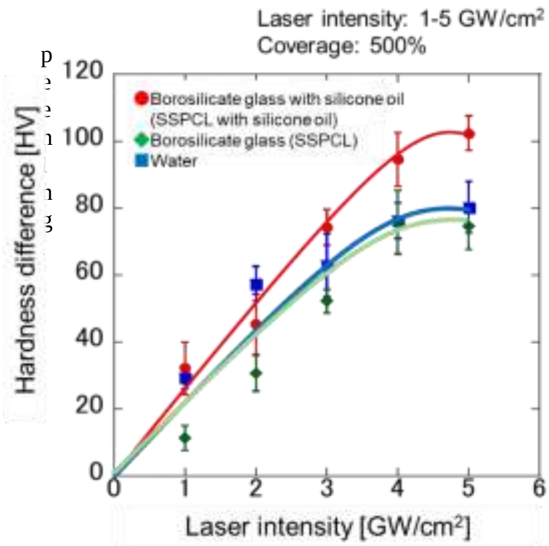

Fig. 6 Surface hardness of laser-peened samples with variousplasma confinement layers.

impedance mismatch should be minimized when the SSPCLis used.

In addition, the Vickers hardness is almost proportional to the laser intensity up to 4 GW/cm^2 and saturates above 4 GW/cm^2 in all plasma confinement layers, as shown in Fig.
6. It is believed that the glass was damaged due to the high- intensity irradiation and that not all of the laser energy reached the sample. Because it has no fluidity, the SSPCL was damaged and could not confine the plasma created by high-intensity laser irradiation. Reduction of the energy due to the damage to the SSPCL surface causes low process ef- ficiency in laser peening. The process window for the laser intensity would be relatively narrow for laser peening with the SSPCL. The plasma must at least be confined by the SSPCL at a laser intensity of around 5 GW/cm^2 and cover- age of 500% in this study. The process window for the laser intensity should be determined appropriately in SSPCL laser peening. Moreover, the SSPCL may be damaged through

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Volume 17 Issue 1Jan 2021

low-intensity laser irradiation below 1 GW/cm^2 even if the plasma can be confined, and therefore the SSPCL would notbe able to be used repeatedly.

Figure 7 shows the residual stress of laser-peened sam- ples obtained by X-ray residual stress measurements in the case of water, the SSPCL and the SSPCL with silicone oil as the plasma confinement layer. The vertical axis and horizon- tal axis are the residual stress and the laser intensity, respec- tively. Positive values indicate tensile stress and negative values indicate compressive stress. As in Fig. 6, the three solid lines represent the results of laser peening with water, the SSPCL alone, and the SSPCL with silicone oil. The re- sults for the residual stress are similar to those for hardness, and the residual stress with the SSPCL is almost the same as that obtained with water. In addition, the residual stress in- creased remarkably when the SSPCL with silicone oil was used. The compressive residual stress reached a maximum at a depth of 20 μm and was observed up to a depth of over 100 μm for all plasma confinement layers. Moreover, the compressive residual stress was about −450 MPa at a depth of 20 μm for the SSPCL with silicone oil. Reducing the

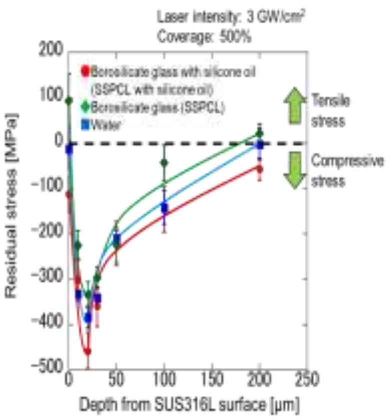

Fig. 7 Residual stress in laser-peened samples with variousplasma confinement layers.

impedance mismatch is beneficial for efficient laser peeningwith SSPCL.

An impedance mismatch always occurs due to the air gap between the metal and solid-state medium and so the plasma is not appreciably confined. In this study, the neces- sity of improving the impedance mismatch in the SSPCL has been demonstrated. Future studies are needed to investigate the possibility of practical use of an SSPCL in industrial ap- plications. Using a liquid medium for the elimination of im- pedance mismatch increases the duty cycle. Ideally, the plasma should be confined by the solid-state medium only. Therefore, the SSPCL should have a shape-following ability to fill the air gap between SSPCL and the target metal, which would enable laser peening by an SSPCL without a liquid. In future work, a gel-like or flexible material that makes smooth contact with the target metal will be examined as anSSPCL in laser peening experiments.

5. Conclusions

In this study, the effect of laser peening with a solid-state medium having a high acoustic impedance as the plasma confinement layer, for efficient laser peening, was investi- gated experimentally. The results can be summarized as fol-lows:

- An SSPCL with silicone oil is more effective than wateras a plasma confinement layer.
- For efficient laser peening, the impedance mismatch should be decreased when using an SSPCL. The air gap be- tween the sample and glass must be filled with a liquid such as silicone oil to reduce the impedance mismatch.
- Greater values of hardness and residual stress were ob- tained when using SSPCL with silicone oil in comparison with water as a plasma confinement layer.
- The Vickers hardness is almost proportional to the laser intensity up to 4 GW/cm^2. However, it saturates above 4 GW/cm^2 in SSPCL due to laser-induced damage.
- The compressive residual stress reached a maximum at a depth of 20 μm and was observed up to a depth of over 100 μm with use of an SSPCL.
- The compressive residual stress was about −450 MPa at a depth of 20 μm for the SSPCL with silicone oil.

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