Effects of Laser Peening Parameters on Plastic Deformation in Stainless Steel

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Laser peening is a surface treatment technique that improves the mechanical performance of metals by producing plastic deformation with a laser-induced shock wave. Current studies on laser peening mainly focus on the magnitude of the compressive residual stress and the hardness of the laser-peened material. Systematic studies on the many parameters that affect laser peening are required to increase the efficiency of the technique. In this study, three factors associated with laser peening are defined and the parameters that govern these factors are identified. The effects of these laser peening parameters on the plastic deformation of stainless steel are described. The laser intensity, coverage (number of laser pulses per unit area), focal spot diameter, and material condition parameters were varied in laser peening experiments. The parameters desirable for efficient laser peening of stainless steel were examined on the basis of the experimental results.

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1. Introduction

Laser peening is a surface treatment technique that improves the mechanical performance of metals [1]. It has been widely used to enhance wear and fatigue resistance in several applications [2]. Laser peening is superior to conventional shot peening since it produces deeper compressive residual stresses and smoother processed surfaces; it is also more suitable for localized processing [3]. These effects are imparted by shock waves that result from the expansion of plasma produced by intense pulsed laser irradiation. At laser intensities exceeding 10^9 W/cm^2, a shock wave is generated by the ignition and explosive expansion of plasma. The plastic deformation caused by this shock wave as it propagates through the metal hardens the metal surface and generates residual compressive stresses in the surface region. The effects of the shock wave can be enhanced by coating the surface of the target material with a confining layer that is transparent to the laser light [4]. Such a layer increases the shock wave intensity because it prevents the laser-produced plasma from rapidly expanding away from the surface, thus creating a high-amplitude, short-duration pressure pulse [4, 5].

The plastically deformed layer is proportional to the product of pressure of shock wave and shock loading time [2], that is

$$E_{\mathrm{LP}} \propto \tau_{\mathrm{S}} \cdot P, \qquad (1)$$

where τ_{S} is the shock loading time and P is the pressure of shock wave. Eq. (1) indicates that the mechanical impulse on the target materials has to be high enough to achieve efficient laser peening. Current studies on laser peening mainly focus on the magnitude of the compressive residual stress and hardness of the materials achieved by the laser peening treatment. However, it is necessary to conduct systematic studies on the numerous parameters that affect laser peening to increase the efficiency of the technique.

In this paper, the parameters desirable for efficient laser peening are considered on the basis of experimental results.

2. Controllable parameters for efficient laser peening

In this section, controllable factors that can increase efficiency of laser peening treatment are examined [6, 7]. The wavelength, pulse width, focal spot diameter, and peak intensity of the laser, as well as the coverage (number of laser pulses per unit area) and F-number of the optics, are all important parameters for efficient laser peening. In addition, the interaction of the laser with the plasma should be considered in order to improve the shock generation. To increase the shock amplitude, it is necessary to use a plasma confinement layer on the target material that is transparent to the laser wavelength. Furthermore, the initial

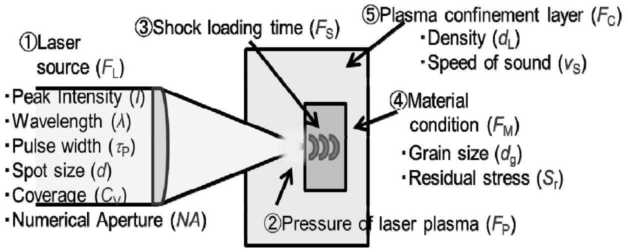

Fig. 1 Laser peening parameters.

properties of the target material, such as the grain size, residual stress, hardness and surface morphology, should be controlled in order to obtain the optimum conditions for laser peening [6-8].

On the basis of the above considerations, five factors associated with laser peening, viz., F_L, F_P, F_S, F_M, and F_C, are defined, pertaining, respectively, to the laser source, laser plasma pressure, loading time of laser-induced shock wave, material condition, and plasma confinement layer, as illustrated in Fig. 1. F_P and F_S are mostly attributable to the laser source, the irradiation conditions and performance of plasma confinement medium, which also directly affect F_L and F_C. Therefore, the main controllable factors in laser peening experiments are F_L, F_M, and F_C. Thus, the expansion of plastically deformed layer on the target material, E_{LP}, can be expressed as the product of these three factors

$$E_{LP} \propto F_L \times F_M \times F_C . \qquad (2)$$

These factors can be controlled by many laser peening parameters. For F_L, the relevant parameters are the peak intensity I, the wavelength λ, the pulse width τ_P, the focal spot size d, coverage C_V, and the F-number of the optics F. For F_M, the two main parameters are the grain size d_g and the residual stress S_r. F_C is a function of the product of the density d_L of the confinement layer and the speed of sound v_S in the confinement layer. Thus, E_{LP} becomes

$$E_{LP} \propto F_L\left(I,\lambda,\tau_P,d,C_V,F\right)\times F_M\left(d_g,S_r\right)\times F_C\left(d_L,v_S\right). \qquad (3)$$

Each laser peening parameter should be optimized for efficient laser peening.

In this study, three factors associated with laser peening are defined with the aim of increasing the efficiency of the technique, and the parameters that control these three factors are identified. More specifically, the peak intensity, focal spot diameter, coverage, and material condition parameters are selected in experiments.

3. Experimental

Figure 2 shows the experimental setup used for laser peening. A nanosecond laser (Nd:YAG) system that delivered a pulse energy of 200 mJ was used. Distilled water was adopted as the material for the plasma confinement layer so that F_C was constant in this study. The water layer thickness is 3 cm, it is sufficient for plasma confinement. Since visible light is not strongly absorbed by water, the second harmonic radiation (wavelength: 0.53 μm) was used in all experiments. The pulse width and repetition rate were fixed to 4 ns and 10 Hz, respectively. SUS316L stainless steels were used as test samples.

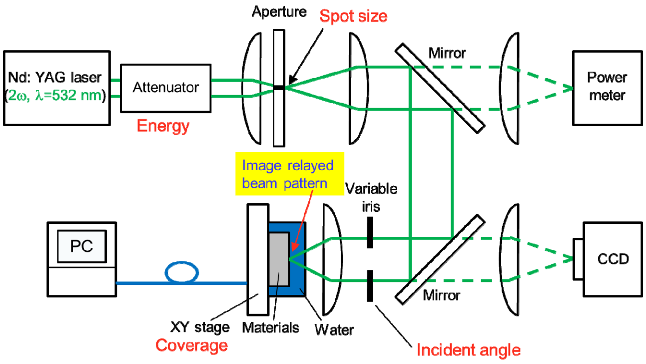

Fig. 2 Experimental setup for laser peening.

The laser beam passed through an energy attenuator and a relay telescope, and was then focused on the sample by a lens with a focal length of 10 cm. The laser beam was incident perpendicularly on the sample. The sample was supported by a holder and immersed in distilled water. The optical arrangement in this study allowed control over a wide range of laser peening parameters, especially F_L. The laser intensity was adjusted with an energy attenuator consisting of a half-wave plate and cross polarizers. Rotation of the half-wave plate changed the polarization, so that the laser intensity could be controlled easily without changing any other laser characteristics. The relay telescope relayed the image at the aperture shown in Fig. 2 to the surface of target samples. The coverage on surface of metals was controlled by XY stage. The coverage means the number of laser shots irradiated per unit area. It is defined as

$$C_V = \frac{A_L N}{A} \times 100\,\% , \qquad (4)$$

where A_L is the area of the laser focal spot, A is the laser-irradiated area, and N is the number of laser shots. The initial properties of the target material influences the effects of laser peening since the plastic deformation produced by any external stress strongly depends on the residual stress, grain size, and number of dislocations. In order to control F_M, an annealing treatment was performed in vacuum by heating the sample to the desired temperature. The relationship between the annealing temperature and laser peening effects was investigated. We adopted a laser peening method that can be used to treat metals without a protective coating [9, 10], which can induce a compressive residual stress in metals by increasing the coverage.

In the estimation of the effects of laser peening i.e., the performance of laser peening, magnitude of compressive residual stress and surface hardening have been measured in our study because compressive residual stress and work hardening are generated as a result of the plastic deformation. Vickers hardness measurements were performed to assess the work hardening produced by laser peening to obtain data for a wide range of laser peening parameters. Residual stress measurements were also conducted to determine the laser peening effects.

4. Experimental results for selected laser peening parameters

4.1 Laser intensity and initial material properties

Figure 3 shows the surface hardness as a function of laser intensity under various heat treatment conditions. The coverage was fixed to 900%. The vertical axis represents the Vickers hardness. The four solid lines show the results for samples annealed at temperatures of 600, 850, and 1100°C, and that of the non-annealed material. The Vickers hardness is linearly proportional to the laser intensity up to 4 GW/cm^2 and saturates above 4 GW/cm^2. Work hardening due to plastic deformation is produced by the stress wave traveling through the sample. Therefore, the Vickers hardness should increase with laser intensity if laser-induced breakdown of water does not occur. The usable laser intensity range is limited for the following reasons. The laser energy reaching the target material has to be reduced to prevent the laser-induced breakdown of water. For green light ($\lambda \approx 0.5$ μm), the laser intensity should be limited to about 6 - 10 GW/cm^2 to prevent such breakdown [11]. Moreover, the penetration of laser light into a high-density plasma is limited by a cutoff phenomenon. Berthe et al. reported that the intensity of laser light transmitted through a plasma saturates for laser intensities exceeding 10 GW/cm^2 [12].

The Vickers hardness saturates above 4 GW/cm^2. It is thought that the hardness properties will be affected by the heat accumulation. The surface is oxidized or melts as a result of the heat, so that the hardness is no longer simply proportional to the laser intensity. For efficient laser peening, the laser intensity should be within the linear range shown in Fig. 3.

The four solid lines seem likely to approach a saturation value in the case of the laser intensity exceeding 10 GW/cm^2. The hardness would be no longer to have material condition dependence in higher intensity laser irradiation. The factor regarding the material condition, F_M does not contribute to improve the efficiency of laser peening treatment in relatively high intensity laser irradiation.

The enhancements of hardness are significant in the annealed samples for the low laser intensity regime. Generally, work hardening occurs through dislocation motion within the crystal grains of the material as a consequence of plastic deformation. Increasing the number of dislocations enables the quantification of work hardening. The laser-induced shock wave can not only cause existing dislocations to move but also produce new dislocations. The crystal grain size and ductility influence the ability of a material to undergo plastic deformation. Annealing can improve ductility, relieve stress, cause softening, and improve the work hardening ability. In addition, dislocation motion in metals tends to occur as a result of grain growth. The grain size grows with increasing annealing temperature in SUS316L stainless steels. A desirable material state, i.e., heat treatment temperature, exists for efficient laser peening in the case of low-laser intensity irradiation.

In order to estimate the residual stresses induced, the samples were characterized through X-ray residual stress measurement. Figure 4 plots the relationship between residual stress and annealing temperature for a metal surface and for a depth of 10 μm from the surface, at a laser intensity of 6 GW/cm^2 and a coverage of 900%. Tensile (compressive) stresses are shown as positive (negative) values. A tensile residual stress is obtained at the sample surface because it melts as a result of the relatively high-intensity laser irradiation. On the other hand, a compressive residual stress is induced inside the metal at a depth of 10 μm. A laser intensity and coverage suitable for generating a compressive residual stress occurred on the surface. The laser intensity should be below 6 GW/cm^2 at a coverage of 900% to avoid melting on the surface. The magnitude of compressive residual stress decreases slightly with increasing annealing temperature. In general, the magnitude of residual stress is proportional to the hardness. Thus, the results shown in Fig. 4 are consistent with the characteristic of hardness shown in Fig. 3.

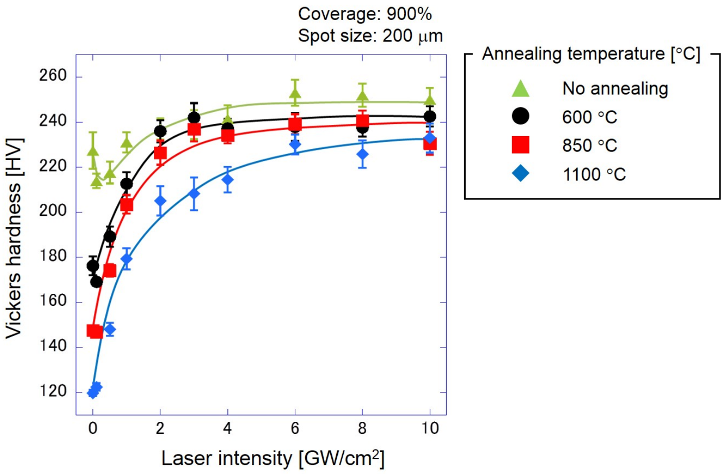

Fig. 3 Relationship between Vickers hardness and laser intensity.

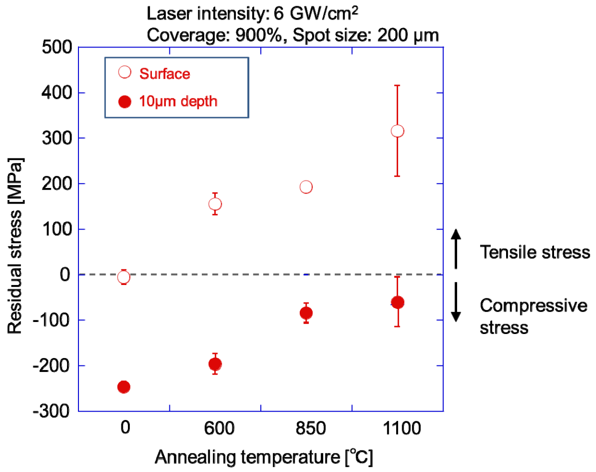

Fig. 4 Relationship between residual stress and annealing temperature.

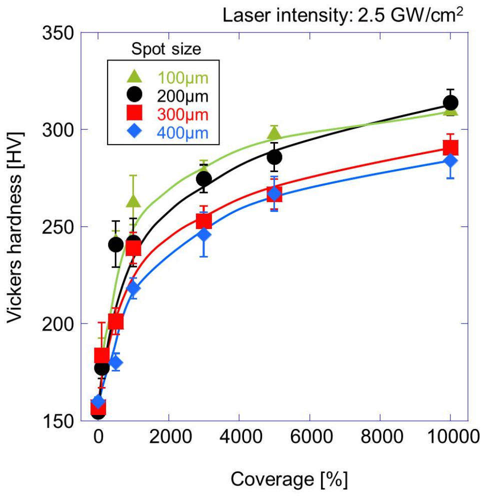

Fig. 5 Vickers hardness vs. coverage.

4.2 Coverage and Spot size

Figure 5 plots the surface hardness as a function of coverage for various spot sizes. The vertical axis represents the Vickers hardness. The four solid lines show the results for laser spot sizes of 100, 200, 300, and 400 µm, respectively. The Vickers hardness is proportional to the coverage up to 1500% and saturates above 1500%. The high coverage indicates the large number of laser shots irradiated per unit area. The hardness increases gently, although the hardness should increase more rapidly with increasing coverage. The laser energy tends to be more varied into heat with increasing coverage. The metal surface is influenced by the heat accumulation. Thus, the surface is oxidized or melts as a result of the heat, so that the hardness is no longer simply proportional to the coverage. In addition, the hardness did not show a strong dependence on spot size.

In order to investigate the residual stresses, the laser-peened sample was characterized through X-ray residual stress measurement. Figure 6 plots the residual stress versus depth from the sample surface for coverages of 900% and 14,400% and a spot size of 400 µm. The compressive residual stress inside the sample is given for both coverages. The compressive residual stress is greater at 14,400% coverage than at 900% coverage. A tensile residual stress is obtained at the surface at a laser intensity of 6 GW/cm^2 and a coverage of 900%, as shown in Fig. 4. In Fig. 6, the tensile residual stress at the surface decreases for a lower laser intensity of 2.5 GW/cm^2. The laser intensity should be lower to prevent the tensile residual stress at the surface for a low coverage of around 900%. On the other hand, a compressive residual stress is obtained at the surface of the sample with a coverage of 14,400%. The results of residual stress measurement indicate that a high coverage, i.e., a large number of laser shots incident per unit area of sample surface is required to transfer the compressive residual stress from the surface to the interior.

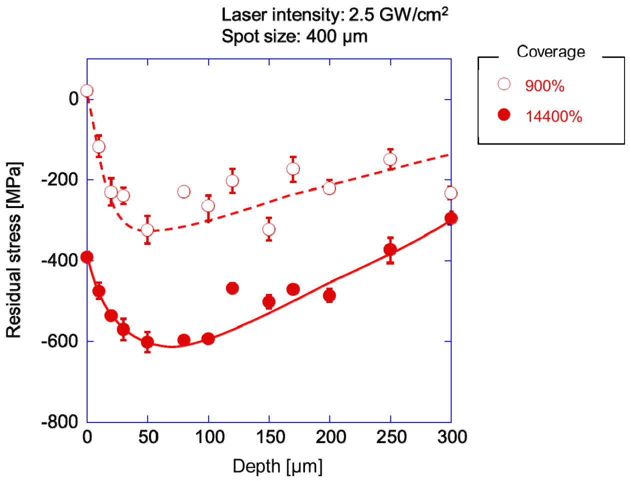

Fig. 6 Residual stress vs. depth at various coverages.

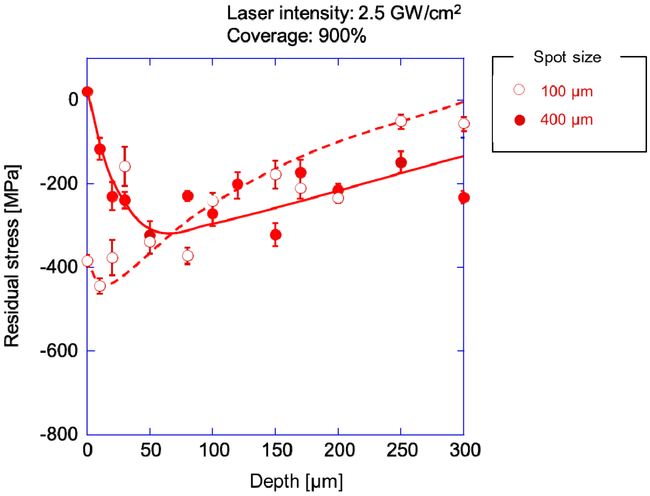

Fig. 7 Residual stress vs. depth for various spot sizes.

Figure 7 shows the residual stress as a function of depth from the surface for spot sizes of 100 and 400 µm. The laser intensity and coverage were found to be 2.5 GW/cm^2 and 900%, respectively. For both spot sizes, a compressive residual stress was obtained. The compressive residual stress at the sample surface was larger for the spot size of 100 µm than for the spot size of 400 µm. The density of the laser-irradiated pulse [pulse/mm^2] varied with the spot size when the coverage was kept constant. A smaller spot size for the same coverage indicates a higher-density pulse in space for the laser irradiation, i.e., more laser pulses are superposed at the sample surface. Therefore, the magnitude of compressive residual stress obtained at the spot size of 100 µm is larger than that at the spot size of 400 µm. As shown in Fig. 6, pulse superposition is important to transfer the compressive residual stress. Thus, the density of the laser-irradiated pulse should be sufficiently high. A small spot size with a high density of laser-irradiated pulses is desirable for obtaining a compressive residual stress at the surface. The maximum compressive residual stress is obtained at a depth of about 30 µm from the surface for a spot size of 100 µm. Thus, a small spot diameter is advantageous in treating thin samples.

The two spot sizes cross each other in terms of residual stress at around a depth of 70 µm. The compressive residual stress inside the sample is obtained at a greater depth in the case of a spot size of 400 µm, suggesting that the shock-affected region is determined by the spot size. In order to achieve effective laser peening, it is important to select a suitable spot size on the basis of the sample thickness.

4.3 Plasma confinement layer

Water was used as a plasma confinement layer in all experiments. The factor associated with the confinement layer, F_C (see Eq. (3)), is also important for efficient laser peening. The confinement ability is determined by the product of two constants: the density of the material and the speed of sound in the material. Therefore, solid materials are more effective as confinement layers. However, most solid-state materials that are transparent to the laser wavelength, such as glass, are damaged by laser irradiation exceeding several GW/cm^2 in intensity. Further work is required to find appropriate confinement layers for efficient shock generation in terms of the density, speed of sound, and threshold for laser-induced breakdown.

5. Conclusion

In this study, five factors associated with laser peening were defined with the aim of increasing the efficiency of the technique, and the parameters that control these five factors were identified. The effects of the parameters on the plastic deformation of the target material were investigated through hardness and residual stress measurements. Experiments were conducted the factors pertaining to the laser source, F_L, and to the material condition, F_M. Thus, the efficient laser peening conditions were obtained in SUS316L.

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