

Laser Peening for Surface Enhancement of Stainless Steel

Hitoshi Nakano^{#1}, Ippei Kitawaki[#], Miho Tsuyama[#]

[#]Department of Electric and Electronic Engineering, Faculty of Science and Engineering, Kindai University,
3-4-1 Kowakae, Higashi-osaka, Osaka 577-8502 Japan

¹hitoshi@ele.kindai.ac.jp

Abstract— Surface enhancement of stainless steel by laser peening has been studied. Especially, in this study, effects of control of plasma confinement layer on have been investigated. The plasma confinement layer for the laser peening is usually used the transparent medium to the laser wavelength, such as a glass and water. The confinement ability depends on the acoustic impedance of the medium. In this study, the acoustic impedance of the water has been controlled by dissolving sodium chloride (NaCl). Second harmonic of Nd:YAG laser having the pulse duration of 4 ns has been used for the laser peening experiments. Commercial SUS316L stainless steel has been adopted as a sample. The samples were investigated under nanosecond laser shock loading in plasma confined by aqueous sodium chloride solution. Vickers hardness test and X-ray diffraction method are used to probe work hardening and residual stress due to plastic deformation induced by laser peening. Through hardness and residual stress measurements, it is found that optimal concentration of the sodium chloride solution has been existed for the laser peening.

Keywords— Laser peening, Plasma confinement layer, Stainless steel, Plastic deformation, Acoustic impedance, Residual stress

I. INTRODUCTION

Laser peening has already demonstrated great potential to enhance the reliability of safety-critical components in a variety of industrial applications. Effects of the laser peening is imparted by the production of a layer of compressive residual stress due to plastic deformation caused by intense shock wave resulting from the expansion of a plasma with a high-peak power laser irradiation. In order to increase the efficiency of the technique, it is essential to have the mechanistic understanding of the influence of the parameters associated with laser peening on the plastic deformation of the material that causes hardening and residual stress production. At laser intensities exceeding 10^9 W/cm², 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 by the laser peening is proportional to the product of pressure of shock wave and shock loading time [2], that is,

$$E_{LP} \propto \tau_s \cdot P, \quad (1)$$

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.

Many researchers have studied about the pressure of laser-induced plasma generated by ablative material in plasma confinement medium [2-6]. Acoustic impedance of plasma confinement layer is important factor which controls the amplitude of the resulting pressure [3]. A water is usually used as the material of plasma confinement layer for the laser peening. The acoustic impedance of the water can be controlled by dissolving some kinds of solute.

In this paper, effects of control of plasma confinement layer on laser peening have been described. Sodium chloride is dissolved in water to control the acoustic impedance of plasma confinement layer. The conditions desirable for efficient laser peening are considered on the basis of experimental results.

II. PRINCEPLE OF LASER PEENING

Figure 1 shows a schematic representation of the mechanism by which laser peening generates residual stress [7]. The surface layer evaporates instantaneously through ablative interaction when a focused-laser pulse is irradiated on the surface of material. Moreover, the vapor is immediately ionized to generate plasma by inverse bremsstrahlung. The laser-induced plasma becomes high pressure state because the liquid prevents it from rapidly expanding from the surface. The plasma confined by liquid generates a shock wave which impinges on the material with an intensity exceeding the yield strength of the material. Then, the plastic deformation is caused by pressing surface of the metal through the dynamic

stresses of the shock wave. As a result, the compressive residual stress layer and the cured layer are formed in the vicinity of the metal surface [2, 6, 8-9]. The depth of the compression reaches 1 mm or more from the laser peened surface.

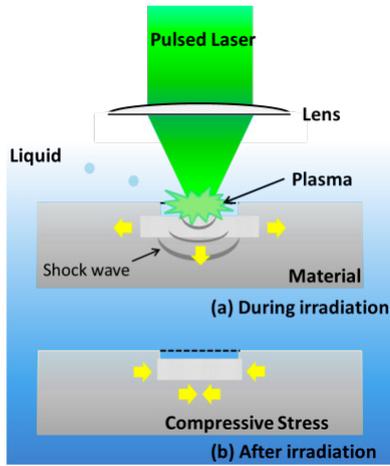


Fig. 1 Mechanism for residual stress improvement using laser-induced shock wave.

III. PLASMA CONFINEMENT LAYER

The difference between confined plasma and free-expansion plasma has been studied by many researchers [2, 5-6]. The plasma pressure is enhanced by the exiting the plasma confinement layer such as water in Fig. 2. Water is applied to suppress the plasma from expanding away off the surface of material thereby increasing the pressure of laser-induced shock wave.

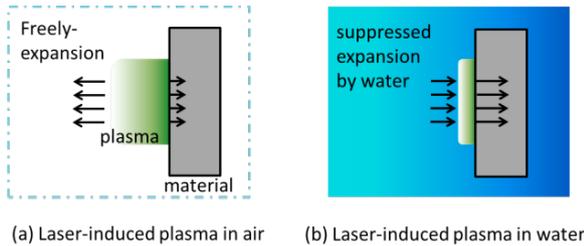


Fig. 2 The difference between confined plasma and free-expansion plasma.

According to Hong's method [5], the pressure of laser-produced plasma P is expressed by

$$P = A \sqrt{\left(\frac{\alpha}{2\alpha + 3}\right) \times \left(\frac{2Z_1 Z_2}{Z_1 + Z_2}\right)} \times I \quad (1)$$

where A is a constant, α is the ratio of the internal energy is converted into thermal energy. Z_i is the acoustic impedance of target material ($i=1$) and the confinement layer ($i=2$). Z_i is defined as $Z_i = d_i v_i$, where d_i and v_i are the density and the sound velocity, respectively. It is shown that acoustic impedance of the plasma confinement layer is dominant factor to determine the pressure of plasma. Performance of plasma confinement layer is shown analytically by the products of two factors depending on

the sound velocity and the density of the plasma confinement layer, that is,

$$F_C \propto Z_2 = d_L \cdot v_s \quad (2)$$

where F_C is the factor regarding the effect of plasma confinement layer on laser peening, d_L is the density of and v_s is the sound velocity of plasma confinement layer.

IV. EXPERIMENTAL METHOD

Second harmonic of Nd:YAG laser having the pulse duration and wavelength of 4 ns and 532 nm, respectively, has been used. We have adopted the laser peening method developed by Y. Sano et al. [10, 11], which can be used to introduce compressive residual stress in metals without a protective coating layer. In addition this method can drastically reduce the laser energy required for peening by increasing the number of laser shots irradiated per unit area.

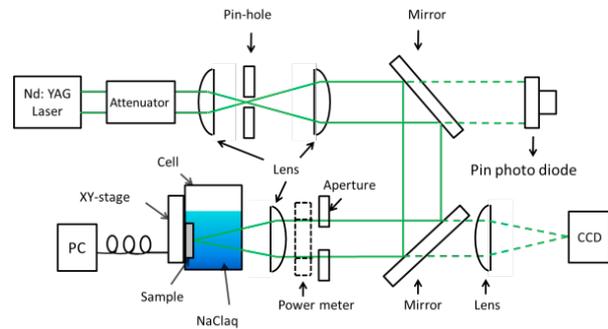


Fig. 3 Experimental layout to obtain laser-peened stainless steel in NaClaq.

Figure 3 shows the schematic diagram of laser peening experiments. Austenitic stainless steel SUS316L with the size of 25 mm × 25 mm × 5 mm was used as a test sample. The samples were electro-polished and stress relief annealed (3 hour treatment at 900 degree) to remove the residual stress before laser irradiation.

In the experiments, imaging optical system by using three convex lenses has been constructed. Image of apodized laser beam at the aperture shown in Fig. 3 is relayed to the surface of the target sample by following optics.

The position of the sample can be controlled using precision XYZ stages connected to a computer. The power meter and CCD camera shown in Fig. 3 can be used to measure the laser energy and laser beam profile on the target surface. The diameter of focal spot was estimated to be 200 μm. The laser peak intensity is fixed to be 5.0 GW/cm². The coverage is kept constant to be 900%. The concentration of NaCl in water for the plasma confinement layer is varied from 0 to 24% in order to increasing the acoustic impedance that depends on the sound velocity and the density. The acoustic impedance is related linearly to the concentration of NaCl [12, 13]. For example, the acoustic impedance of sodium chloride solution 24% in concentration is about 1.4 times larger than the water. Laser irradiated region is adjusted to be 10

mm × 10 mm by controlling the position of the XY stages. The repetition rate of the laser pulse is 10 Hz.

The work hardening resulting from laser peening treatment was evaluated using the Vickers micro-hardness test. The hardness of the surface was measured by using a load of 1.961 N for 10 s. The residual stress was measured by X-ray diffraction method [14] using a $\sin^2\psi$ law, in which the X-ray beam diameter was about 1 mm.

V. RESULTS AND DISCUSSION

Figure 4 shows the Vickers hardness of the surface of SUS316L as a function of the concentration of NaCl in water. The hardness is determined by the average of ten indentations at the same laser irradiated region. Initial surface hardness was 162 HV. There was increase in hardness in case of dissolving sodium chloride. The hardness of surface increased linearly with increase of the concentration of NaCl up to 6% in Fig 4. The hardness decreased with the concentration of NaCl exceeding about 6%. In addition, it was subjected to residual stress measurement in order to ascertain whether the pressure has been introduced.

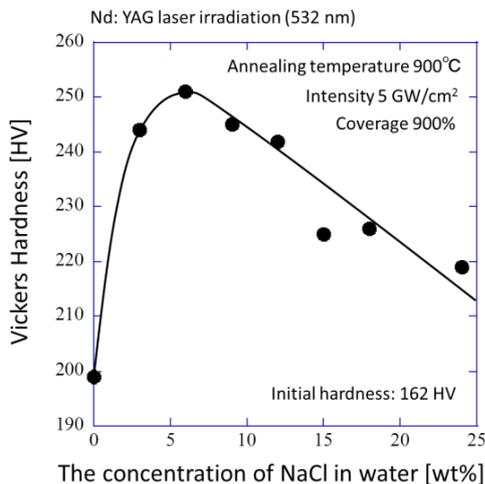


Fig. 4 Surface hardness as a function of the concentration of NaCl in water.

Figure 5 shows residual stress as a function of the concentration of NaCl in water on 20 μm in depth. The surface is polished 20 μm in order to remove the tensile stress appeared in the surface. The maximum value of the residual stress is obtained at the concentration of 9%. The residual compressive stress decreased with the concentration of NaCl exceeding about 9%. Residual stress had the same behaviour to the concentration of NaCl as the results of hardness profile shown in Fig. 4.

Figure 6 shows residual stress as a function of the depth for various concentration of NaCl. A tensile stress remains on the surface of sample. In Fig. 6, it is suggested that the tensile stress on the sample surface remained due to thermal effect [2]. A residual compressive stress is given over 250 μm in depth. Residual stress distribution shows a similar trend at each concentration.

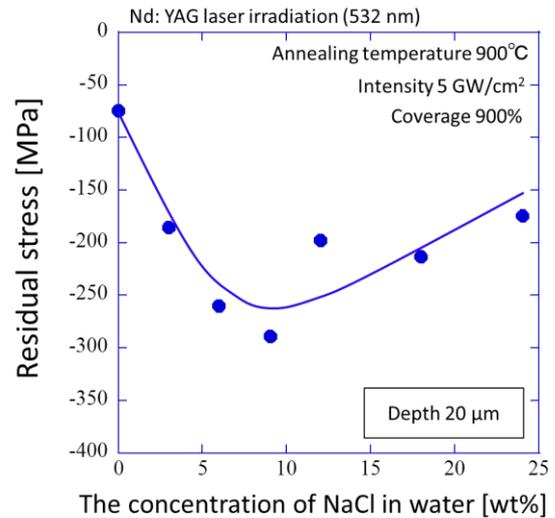


Fig. 5 Residual stress as a function of the concentration of NaCl in water.

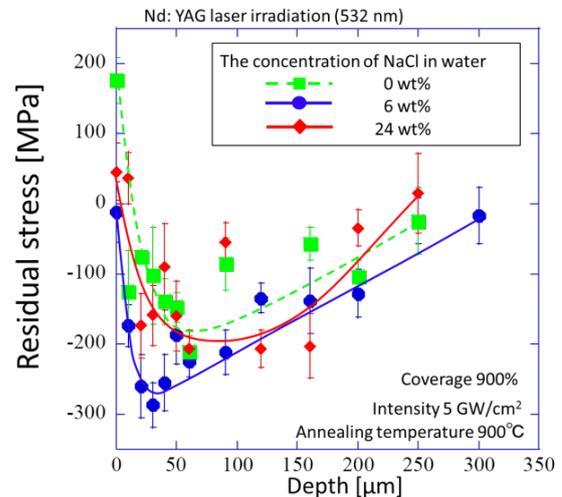


Fig. 6 Residual stress as a function of the depth under various concentrations of NaCl in water.

From the results shown in Fig 4-6, it was observed that enhances the hardness and residual compressive stress by controlling the speed of sound and density of the plasma confinement layer. Desired concentration of NaCl for laser peening should be around 6%. According to Eq. (1), pressure is expected to increase with increasing the acoustic impedance of confinement layer, amount of the plastic deformation is increased. Therefore, the experimental results indicates that hardness and residual compressive stress are increased owing to improvement of the ability of plasma confinement layer. However, laser peening did not efficient with the concentration of NaCl exceeding about 6%. This is considered to be due to the influence of optical breakdown of aqueous sodium chloride solution at under irradiated laser beam. The conductivity increases by dissolving the sodium chloride to water, there is a possibility that the change of the absorption characteristics, and the optical breakdown

becomes likely to occur. Since the energy of the laser did not reach efficiently the sample, desirable laser-induced pressure was not obtained. In the future, there is a need to examine the conductivity of the sodium chloride aqueous solution, and measure laser-induced pressure.

VI. CONCLUSIONS

Effect of control of plasma confinement layer on laser peening has been investigated through hardness and residual stress measurements. The reasonable concentration of NaCl solution as a plasma confinement material is to be 6% for introducing efficient plastic deformation.

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