Femtosecond and Nanosecond Laser Peening of Stainless Steel

Hitoshi NAKANO[*1], Miho TSUYAMA[*1], Sho MIYAUTI[*1], Toshiya SHIBAYANAGI[*2], Masahiro TSUKAMOTO[*2] and Nobuyuki ABE[*2]

[*1] *School of Science and Engineering, Kinki University, 3-4-1 Kowakae, Higashi-osaka, Osaka 577-8502, Japan*
E-mail: hitoshi@ele.kindai.ac.jp
[*2] *Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*

We have compared the results of laser shock peening obtained by using a femtosecond laser with those obtained by using a nanosecond laser. Commercial SUS304 stainless steel was used as the test sample. The sample was subject to femtosecond or nanosecond laser-shock loading in a plasma confined by water. The Vickers microhardness test was used to evaluate the work hardening in the sample due to the plastic deformation induced by the laser peening. The surface hardness of stainless steel increased linearly with laser energy. The results of this study indicate that the extent of work hardening is similar for both femtosecond and nanosecond laser peening.

DOI:10.2961/jlmn.2010.02.0014

Keywords: Keywords: laser peening, femtosecond laser, nanosecond laser, stainless steel, hardness

1. Introduction

Laser peening is a surface treatment technique that is used to improve the mechanical performance of metals. For instance, it can be used to increase the resistance of a metal to crack initiation, extend the fatigue life, and enhance the fatigue strength [1–3]. This treatment is imparted by shockwaves resulting from the expansion of high-pressure plasma generated by an intense pulsed laser. Most previous studies on laser peening have used nanosecond pulsed lasers [1–3].

In a previous study, we experimentally investigated the feasibility of femtosecond laser peening of metals [4]. A femtosecond laser has the potential to generate a strong shockwave in a target material. However, there have been few studies on laser peening using femtosecond lasers. D. Lee carried out femtosecond laser peening using a 200 fs pulse on low carbon steel with top coating materials [5]. However, they could not confirm the potential of femtosecond laser peening. We carried out femtosecond laser peening of stainless steel [4]; to the best of our knowledge, it was the first published paper on femtosecond laser peening. Nonetheless, a systematic study of femtosecond laser peening has not yet been conducted.

In this paper, we report the experimental results of the femtosecond laser peening of stainless steel, and compare these results with those obtained by conventional nanosecond laser peening. The Vickers microhardness test has been used to evaluate the work hardening caused by laser peening. Furthermore, the dependences of hardness on various laser parameters were examined.

2. Femtosecond laser peening

Figure 1 shows a schematic representation of the laser peening of metals. In laser peening, a shockwave has to be induced in the target metal by generating plasma on its surface. At laser intensities exceeding 10^{10} W/cm^2, a shockwave is generated due to the ignition and explosive expansion of the plasma. The plastic deformation caused by the shockwave while propagating through the metal results in the hardening of the metal surface and the generation of a surface with residual compressive stresses. The effect of the shockwave can be enhanced by coating the surface of the target metal with a confining layer that is transparent to the laser beam [6]. The use of such a layer leads to an increase in the intensity of the shockwave because it prevents the laser-produced plasma from expanding rapidly away from the surface, thus creating a high-amplitude short-duration pressure pulse. In laser peening, including femtosecond laser peeling, water, quartz, or glass is generally used as the transparent layer.

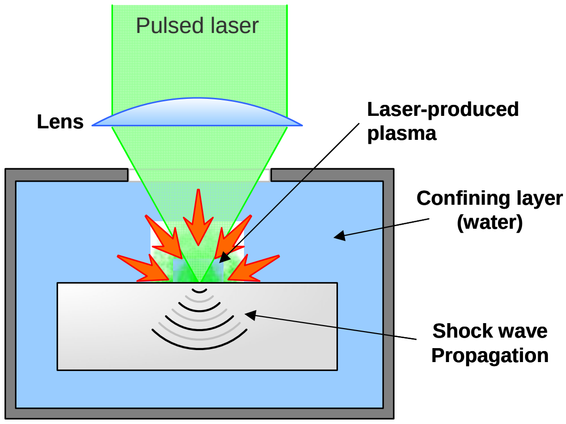

Fig. 1 Schematic representation of the laser peening.

The femtosecond laser has the potential to generate high-pressure plasma. The relation between pressure P_L induced by an intense laser and the plastically deformed layer L_p can be represented as [5, 7]

$$L_p \propto \tau_s \cdot P_L \ , \qquad (1)$$

where τ_s is the shock loading time. This expression indicates that the laser peening effect is determined by the mechanical impulse on the target materials. The pressure P_L is proportional to $I_0^{1/2}$, where I_0 is the laser intensity [7]. A short pulsed laser results in a short shock loading time [8]. Therefore, the femtosecond laser may be not effective for laser peening. However, a high-pressure plasma can easily be obtained by femtosecond laser irradiation at low energy fluence because of its ultra-intense light, which then generates a strong shockwave. Therefore, the high P_L can compensate for the short τ_s. In addition, many studies have shown that a femtosecond laser is an effective tool for precision material processing because of the minimal thermal damage to the laser-irradiated area. Femtosecond laser peening also results in a comparatively smoother surface than nanosecond laser peening. Moreover, because the femtosecond laser beam has an ultrashort pulse duration, it does not interact with the plasma; hence, there is no absorption of the laser energy by the plasma. This allows the entire energy of the laser to be deposited on the target material [9]. Furthermore, femtosecond laser irradiation produces a stationary shock wave that effectively propagates in a metal. Therefore, it may be possible to realize effective laser peening using a femtosecond laser.

3. Experimental

A femtosecond laser system (Ti:sapphire, IFRIT, Cyber Laser) and a nanosecond laser system (2nd harmonic of Nd:YAG, E308, Spectron) are used in the experiments. The wavelengths of these respective lasers are 800 nm and 530 nm. Both laser beams are plane polarized after passing through a polarizer in the laser system.

Figure 2 shows the experimental arrangement for laser peening. Austenitic stainless steel SUS304 having dimensions of 2 cm × 2 cm × 0.5 cm was used as the test sample. The test sample was electropolished and annealed perfectly for 3 h at 1100°C to remove any residual stress prior to laser irradiation. We adopted the laser peening technique developed by Y. Sano et al. [3, 10]. This technique can be used to introduce compressive residual stress in metals without requiring a protective coating on the target materials. In addition, it can drastically reduce the laser energy required for peening by increasing the number of laser shots irradiated per unit area.

The laser beam passes through two beam splitters following which it is focused on the sample by using a lens having a focal length of 10 cm. The sample is supported by a holder and immersed in distilled water for plasma confinement. The position of the sample can be controlled using precision XYZ stages connected to a computer. The energy monitoring system and the CCD camera shown in Fig. 2 were used to measure the energy and laser-beam profile on the sample.

In femtosecond laser irradiation, the pulse duration is fixed to be 191 fs at a nominal wavelength of 800 nm. The repetition rate of the laser pulse is adjusted to be 100 Hz to achieve a reasonable processing time. The focal spot is elliptical, and its dimensions are estimated to be 40 μm ×80

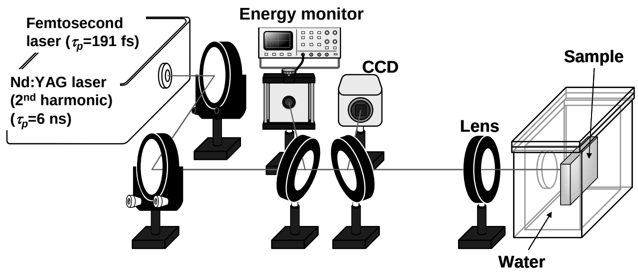

Fig. 2 Experimental arrangement for laser peening.

μm. The average laser fluence is varied from 2 to 10 J/cm^2 by rotating the half wave plate placed between the polarizers. In nanosecond laser irradiation, the pulse duration is fixed to be 6 ns through Q-switch mode operation. The repetition rate is adjusted to be 10 Hz. The focal spot size is measured to be 100 μm. The average laser fluence is varied from 5 to 20 J/cm^2. In addition, coverage F_C [3] is also adopted as a laser irradiation parameter, and it is given by

$$F_c = \frac{A_L N}{A} \times 100 \quad [\%] \ , \qquad (2)$$

where A_L is the area of the laser focal spot; A, the laser-irradiated area; and N, the number of laser shots.

The work hardening resulting from laser peening was evaluated using the Vickers microhardness test. The hardness of the surface and side surface was measured by using a load of 0.1 N for 30 s. In order to suppress the work hardening induced by all other effects except laser peening, we did not apply any mechanical forces on the sample after laser irradiation. The laser was incident from an edge and it was moved toward the center of the sample, as shown in Fig. 3. The laser-generated shock wave affected both the surface and its side surface during its propagation. Therefore, hardness profile measurements do not require any mechanical work for creating a cross section. Prior to laser peening, the hardnesses of both the surface and the side surface of the sample were approximately 200 Hv. In addition, microhardness profiles were obtained for various laser

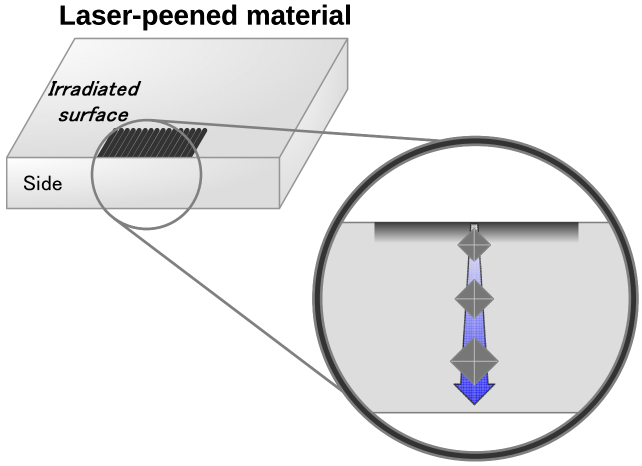

Fig. 3 Vickers micro hardness is used to prove the work hardening caused by laser peening.

parameters.

4. Results and discussions

Figure 4 shows the Vickers microhardness of the surface of SUS304 as a function of the energy fluence for femtosecond and nanosecond laser irradiation. Pulse widths of 191 fs and 6 ns were used for the femtosecond and nanosecond lasers, respectively. The coverage for both lasers was fixed at 2000%. We can observe that both laser irradiations caused a change in the hardness, as indicated by the plastic deformation in stainless steel. The femtosecond laser has the potential to change the mechanical properties of stainless steel. The hardness of the surface increases linearly with the energy fluence. The femtosecond laser was slightly better at hardening, however, there was no remarkable difference between the results of both laser irradiations. A comparison of the depth profiles (relation between hardness and the depth from the surface of sample) for both lasers is shown in Fig. 5. In the experiments, the energy fluence and coverage were adjusted to be 10 J/cm^2 and 2000%, respectively. The dashed line in this figure indicates the normal hardness before laser irradiation. The extent of work hardening due to plastic deformation is similar for both femtosecond and nanosecond laser peening using the present laser parameters. Since the femtosecond laser does not interact with the laser-produced plasma, the plasma does not absorb any laser energy; therefore, the entire energy of the laser is deposited on the target material. The optical break down of the water used for confinement may limit the possibility of effective peening by femtosecond laser irradiation. However, femtosecond laser peening was not found to have any advantages, at least in the hardness measurements.

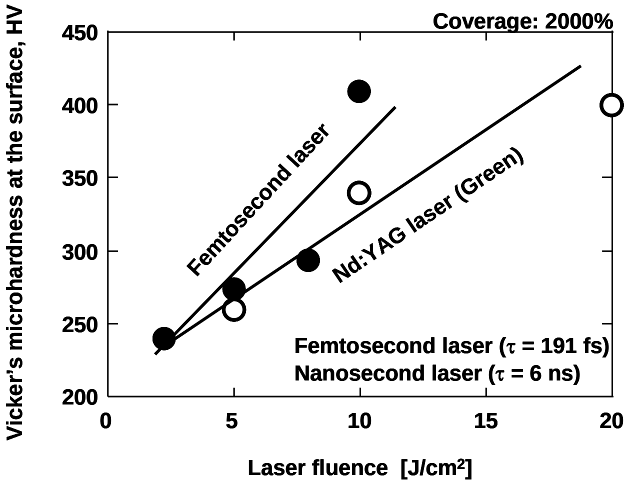

Fig. 4 Vickers micro hardness as a function of energy fluence for femtosecond and nanosecond laser.

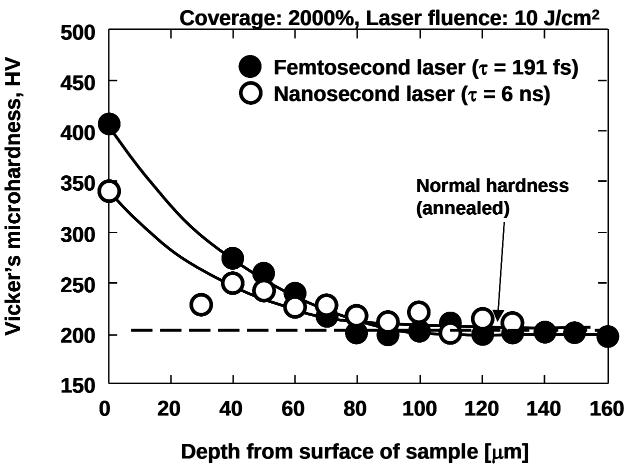

Fig. 5 Vickers micro hardness as a function of depth for femtosecond and nanosecond laser.

If the mechanical impulse $\tau_s \cdot P_L$ is similar for both femtosecond and nanosecond laser irradiation with the same energy fluence, then the extent of plastic deformation induced by both lasers is also similar. Further, the hardness caused due to femtosecond laser peening is almost similar to that caused by nanosecond laser peening. The shock loading time τ_s in femtosecond laser peening must be shorter than that in nanosecond laser peening [8]. The results of the hardness measurements indicate that the decrease in τ_s may be compensated by the increase in P_L induced by femtosecond laser irradiation. The results do not include possible parameter changes for improving laser peening using a femtosecond laser. The process parameters used in this study can be optimized for effective femtosecond laser peening. Further studies are required to investigate the shock loading time and the laser absorption efficiency in femtosecond laser-irradiated metals. It is also necessary to investigate the residual stress in femtosecond laser-irradiated metals and their microstructure to establish the advantages of femtosecond laser peening.

5. Conclusion

We have compared the work hardening of stainless steel by femtosecond and nanosecond laser irradiation to investigate the feasibility of femtosecond laser shock peening. The surface hardness of stainless steel increased linearly with the laser energy of femtosecond and nanosecond lasers. The extent of hardening due to femtosecond laser peening is almost similar to that due to nanosecond laser peening.

Acknowledgments

We wish to thank Satoshi Yamatani for his technical assistance during this study.

References

[1] K. Ding and L. Ye: "Laser shock peening" (CRC press WP, 2006) Chapters 1 and 2.

[2] P. Peyre, L. Berthe, X. Scherpereel, and R. Fabbro: J. Mater. Sci., **33**, (1998) 1421.

[3] Y. Sano, M. Obata, T. Kubo, N. Mukai, M. Yoda, K. Masaki, and Y. Ochi: Mater. Sci. Eng. A, **417**, (2006) 334.

[4] H. Nakano, S. Miyauti, N. Butani, T. Shibayanagi, M. Tsukamoto, and N. Abe: J. Laser Micro/Nanoeng., **4**, (2009) 35.

[5] D. K. Lee and E. K. Asibu Jr: Proc. ICALEO 2008, p. 125.

[6] R. Fabbro, J. Fournier, P. Ballard, D. Devaux, and J. Virmont: J. Appl. Phys., **68**, (1990) 775.

[7] R. Fabbro, P. Peyre, L. Berthe, and X. Scherpereel: J. Laser Appl., **10**, (1998) 265.

[8] T. Sano, H. Moria, O. Sakata, E. Ohmura, I. Miyamoto, A. Hirose, and K. F. Kobayashi: Appl. Sur. Sci., **247**, (2005) 571.

[9] B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry: Phys. Rev. B, **53**, (1996) 1749.

[10] Y. Sano, K. Akita, K. Masaki, Y. Ochi, I. Altenberger, and B. Scholtes: J. Laser Micro/Nanoeng., **1**, (2006) 161.

(Received: July 9, 2009, Accepted: February 27, 2010)