Compressive residual stress generation process by laser peening without pre-coating

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Abstract

Laser peening without pre-coating has been applied to water-immersed specimens of high tensile strength steel. In order to understand the generation process of compressive residual stress, specimens with various laser irradiation patterns, i.e., single spot, line scanning and area scanning, were prepared. Detailed distributions of residual stress on the specimens were measured using synchrotron radiation. Large tensile residual stresses, which might be caused by the thermal effect of the laser pulse, were observed in the center region on the single spot. It decreased towards the edge of the spot, and changed to compression around the spot. The compression became larger with the increasing pulse numbers irradiated on the same spot. In the line scanning, a tensile residual stress was observed in the final spot of the line, which decreased and changed to compression as the distance from the final spot increased. The residual stress on the area scanning was compression as a whole. It was estimated that the compressive residual stress in the area scanning would be generated from the overlapping effect of the compressive field made around each laser spot. The residual stress generated by laser peening without pre-coating is considered to be the superimposition of the tensile and the compressive components due to thermal effect and plastic deformation, respectively.
Keywords: laser peening, surface residual stress, single pulse, line irradiation, laser pulse density, x-ray stress measurement, synchrotron diffraction.

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1 Introduction

Laser peening is one of surface treatment technologies to improve fatigue strength and resistance to stress corrosion cracking (SCC) [1, 2]. Laser peening utilizes a mechanical interaction between the surface of material and plasma caused by the irradiation of a nanoseconds-order laser pulse. Laser peening introduces compressive residual stress in surface layer (more than 1 mm in depth) and, therefore, has been applied to reactor core shrouds of nuclear power plants to prevent SCC [3].

Our laser peening method is able to generate the compressive residual stress on the material surface without any ablative coating [4], and the laser power is relatively low. Therefore the treatment process is simple and the laser pulses can be led easily through optical fibre. However, the residual stress generation mechanism is not simple because the thin surface layer of material is exposed to the high temperature plasma and it can cause a tensile residual stress on the component.

Mukai et al. reported that the surface residual stress changes to the compression side when the number of laser pulses irradiated per unit area was increased. Recently, microscopic distributions of residual stress on a single laser spot were measured using synchrotron radiation source [5, 6, 7]. As a result, the tensile residual stress was observed on the surface of the center of the single laser spot. The phenomenon that the residual stress changes from tension at the first pulse to compression in the area irradiation is considered to be a key factor to clarify the residual stress generation mechanism.

In this study, laser pulses were irradiated on the same spot to investigate the effect of overlapping of laser pulses. A line scanning specimen was also prepared to investigate the effect of offset over lapping of laser pulses. Microscopic distributions of residual stress were measured on the surface of these specimens to discuss the residual stress generation mechanism.

2 Fundamental mechanism of residual stress generation by laser peening

Fig. 1 shows the fundamental process of laser peening. Laser beam focused by a lens is irradiated on a specimen surface in water. The material surface layer becomes plasma if the power density of the laser pulse at the material surface exceeds the threshold of the ablation of the material. The inertia of water prevents the expansion of the plasma, and the energy of the plasma concentrates in a narrow space. The resulting plasma pressure becomes 10∼100 times higher than that in air and it reaches 1 to 10 GPa [8]. The shock wave is generated by this pressure, and it propagates in the material. Plastic deformation occurs near the surface of the material due to the dynamic stress of the shock wave, and the material is hardened through the process. The compressive residual stress is generated by the elastic restraint from the un-deformed region. The generation of the compressive residual stress has been explained basically by this mechanism, since the depth profile of the residual stress by laser peening is well reproduced by elastic-plastic dynamic simulations.

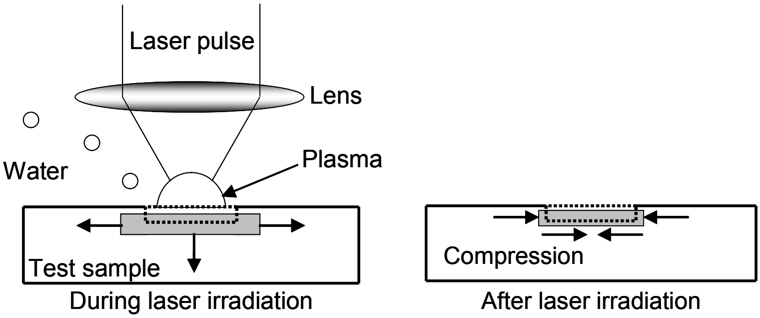

Figure 1: Fundamental process of laser peening.

3 Experimental procedure

3.1 Material and specimens

Material used in this study is high tensile strength steel, HT1000. Table 1 and Table 2 show the chemical compositions and the mechanical properties, respectively. Fig.2 shows the micrograph of the HT1000 surface. The grain size is around 10 μm or less, so it is suitable for the specimen of microscopic X-ray stress measurements. The dimensions of the specimens are 20 mm × 80 mm with the thickness of 15 mm and 28 mm × 30 mm with the thickness of 17 mm. To minimize the effect of residual stress by machining, the electrolytic polishing was applied on the surface of the specimens prior to laser irradiation.

Table 1: Chemical compositions of HT1000.

C	Si	Mn	P	S	Mo	Nb	V	Cr
0.13	0.25	0.92	0.011	0.001	0.39	0.02	0.04	0.87

Table 2: Mechanical properties of HT1000.

Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]
965	1055	23

3.2 Laser peening conditions

The schematic of experimental setup for laser peening is shown in Fig.3. The fundamental wave of a Q-switched Nd:YAG laser (λ = 1.06 μm) was frequency-doubled to a water-penetrable wave (λ = 532 nm) by a second harmonic generator with a nonlinear optical crystal. The laser beam was focused by a lens and irradiated on a specimen in a water jacket through an optical window. The diameter of the laser spot was about 1 mm. The specimen was fixed on a specimen holder and driven to x- and y-directions in the water jacket during laser irradiation.

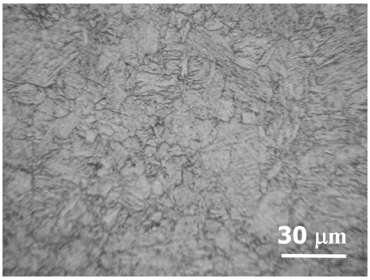

Figure 2: Micrograph of HT1000 specimen surface.

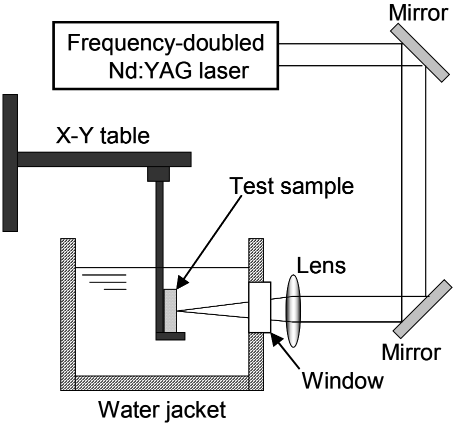

Figure 3: Experimental setup of laser peening.

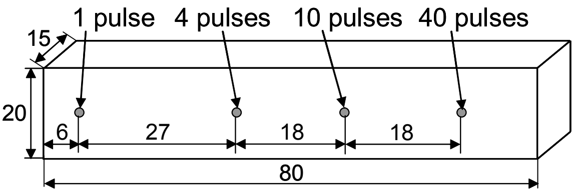

Figure 4: Scheme of pulse laser irradiation on the same spot on HT1000 specimen.

Fig.4 illustrates the single spot specimen where laser pulses irradiated at the same point 1, 4, 10, and 40 times. The line and area scanning were performed as shown in Fig.5 (a) and (b). The lines with pulse densities of 1, 5, 10 and 100 /mm were prepared in the line scanning, changing the scanning speed. In the area scanning, an area of 10 × 10 mm^2 is irradiated by scanning laser pulses two-dimensionally, as shown in Fig.5 (b). The coverage was 800% which was defined in the same way in shot peening. The laser irradiation conditions are summarized in Table 3.

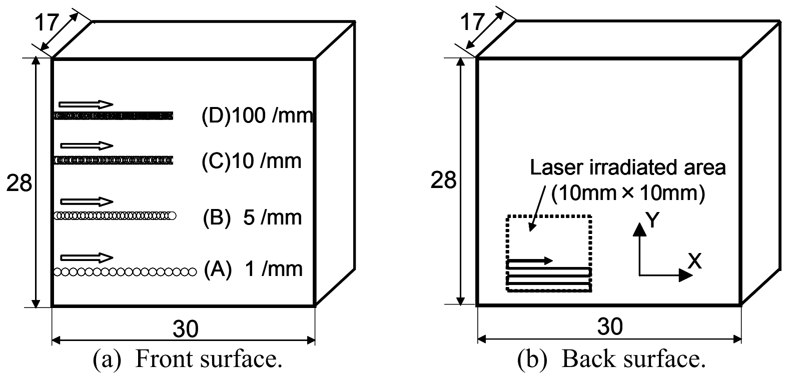

Figure 5: Laser pulses irradiation scheme (Numerals in (a) mean the number of laser pulses per unit length. Arrows mean the laser scanning direction).

Table 3: Laser peening conditions on HT1000 specimens.

Material	HT1000
Pulse energy	215 mJ
Spot diameter	1.0 mm
Pulse duration	8 ns
Coverage	800% (Fig,5 (b))
Pulses irradiated per unit length	1 /mm (A) 5 /mm (B) 10 /mm (C) 100 /mm (D)
Single pulse	1, 4, 10 and 40 pulses

3.3 Residual stress measurement

The microscopic residual stress distributions near single laser pulse spot, laser irradiated line and laser irradiated area were measured on the HT1000 specimens using the synchrotron radiation source at the beam line 3A of Photon Factory, KEK, Tsukuba, Japan. Synchrotron radiation is suitable for the microscopic residual stress measurement required in this research because the intensity of the radiation is much higher than that of the typical laboratory X-ray. The wavelength used was 0.228 nm. α-Fe211 diffraction was measured. The X-ray irradiated area was ϕ0.2 mm or 0.5 mm in diameter. Residual stress was derived by the $\sin^2\psi$ method. X-ray stress constant, K, is assumed to be the mean value of the calculated ones using Reuss and Voigt models and the elastic compliance of a single crystal of α-Fe. The X-ray stress measurement conditions are summarized in Table 4.

Table 4: Conditions of X-ray stress measurement.

X-ray source	Synchrotron radiation KEK, PF BL3A
Material	HT1000
Diffraction plane	α- Fe211
Wavelength	0.228 [nm]
Diffraction angle	154 [deg]
Detector	PSPC
Irradiated area	ϕ 0.2 [mm] or ϕ 0.5 [mm]
X-ray stress constant, K	-353 [MPa/deg]

4 Experimental results

4.1 Surface residual stress distributions on the overlapped laser spot

Fig. 6 shows the schematic illustration of the measuring positions of surface residual stress in and around the overlapped laser spot. The X-ray irradiated area was 0.2 mm in diameter.

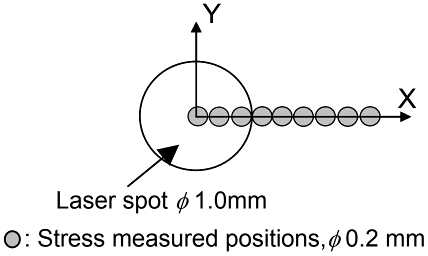

Figure 6: Schematic illustration of residual stress measurement positions in and around a single pulse laser irradiated spot (see Fig. 7).

Fig. 7 shows the surface residual stress distributions along X-axis of Fig. 6. Large tensile residual stresses of about 600-800 MPa were observed in all the

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laser spots with 1 to 40 pulses. The tensile residual stresses decreased toward the edge of laser spot, and changed to compression in the outside of the spot. The compression was about -200 MPa in the single pulse spot. When the number of laser pulses increased, the compression increased at 0.3mm outside from the edge of laser spot. The maximum compressive residual stress reached to -600 MPa for 40 pulsed spot.

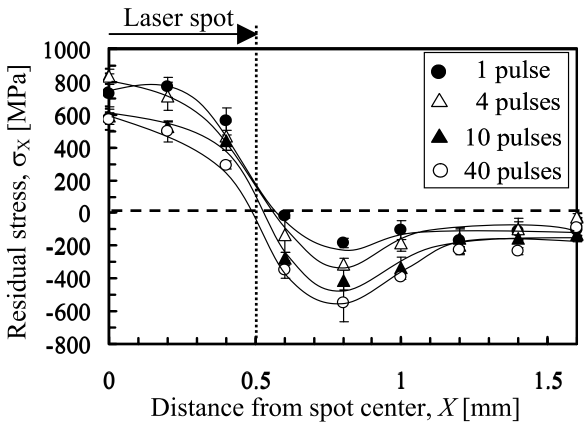


Figure 7: Surface residual stress distribution in and around the laser spots irradiated 1, 4, 10 and 40 pulses at the same position.

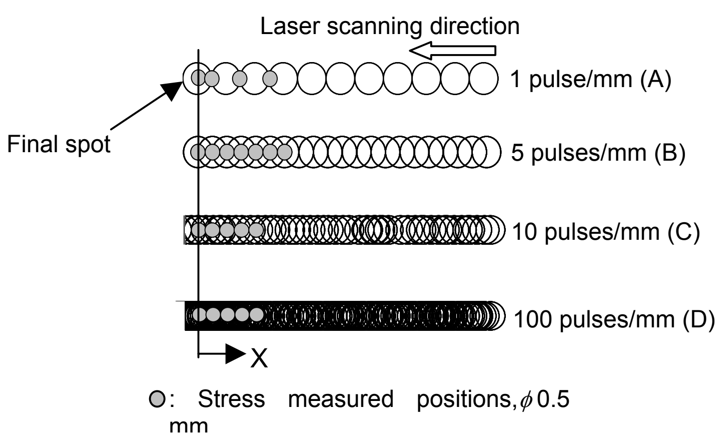


Figure 8: Schematic illustration of residual stress measurement positions on the center line of laser irradiated line.

4.2 Surface residual stress distributions in laser irradiated line and area

The interaction of adjoined laser spots was examined using the line-scanned specimen. Fig.8 shows the positions of residual stress measurement on the laser irradiated line. Fig.9 shows the surface residual stress distributions along the lines. The horizontal axis of the figure shows the distance from the center of the final laser spot center of each line. The X-ray irradiated area was 0.5 mm in diameter. The tensile residual stresses were observed near the final spot for the cases A, B and C. The tensions decreased with increasing the distance from the final spot. The tensile residual stress was decreased with increasing the number of laser pulses per unit length, and it changed to the compression side in case of D with the 100 pulses/mm irradiation density. On the area-scanned specimen with the coverage of 800%, the surface residual stress was compression with about -150 MPa.

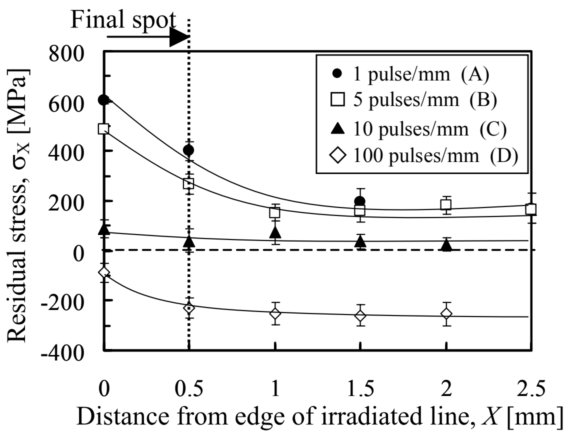


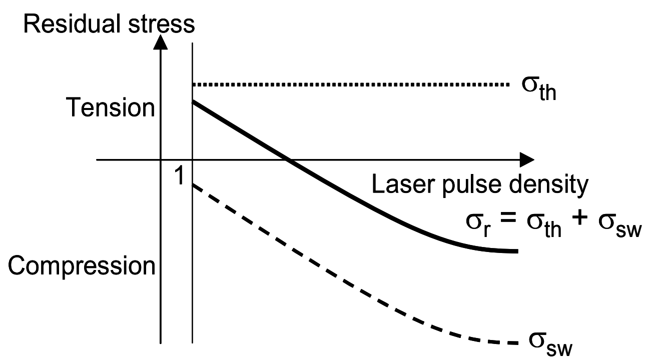
Figure 9: Surface residual stress distributions along the center of laser irradiated line.

5 Discussion

The residual stress at the center of the single spot was tensile even if laser pulses were irradiated 40 times at the same position (Fig. 7). Meanwhile when the laser pulses were scanned in a line as shown in Fig. 9, tensile residual stresses were rapidly decreased with increasing distance from the final spot. These facts mean the overlapping of laser pulses at the same position dose not generate compression at the center of laser spot, on the other hand the off-center overlapping of laser pulses decreases the tension as shown for the lines A, B and C in Fig. 9. The reason of this phenomenon is considered that the compressive residual stress region around laser spot overlaps with tension region at the spot center of the adjoining spot by off-center overlapping.

When the irradiation density was increased to 100 pulses/mm (Line D), the residual stresses changed to compression. However, although the irradiation density per unit length of the area irradiation was 3.2 pulses/mm, the residual stress was compression. These facts mean that an off-center overlapping of laser scanning lines is also important to generate higher compressive residual stresses.

Our laser peening process does not use any pre-coating. Therefore, the material surface is exposed to high temperature plasma, and the resulting surface residual stress depends mainly on the balance of the compressive stress component generated by cold working due to high-pressure laser plasma and the tensile stress component generated by rapid cooling due to thermal effect. Thermally affected depth is only several micrometers [9] and the effect seems to be reset pulse by pulse. However, the plastic deformation caused by cold working can be accumulated [10]. Therefore, the tensile component might be constant and the compressive component increases when the laser pulse density increases. Thus, the whole stress level is changed to the compression side, when the number of laser pulses increases, as shown in Fig. 10.



σ_r: Surface residual stress on laser peened area
σ_{th}: Tensile stress component generated by thermal effect
σ_{sw}: Compressive stress component generated by accumulation of compressive residual stress around laser spot

Figure 10: Schematic of the residual stress generation mechanism on laser peening without pre-coating.

6 Conclusion

Overlapped single laser pulse, line irradiation and area irradiation were performed on high tensile strength steel, HT1000 and the residual stress distributions near the irradiated spot, line and area were measured using a synchrotron radiation source. The results obtained through the experiments are summarized as follows:

(1) Residual stress was tension in the single spot even if 40 laser pulses were irradiated at the same position. Compressive residual stress was observed in the outside of the spot.

(2) Off-center overlapping of laser pulses generates the compressive residual stress on the surface of HT1000 because the compressive stress region at the

outside of laser spot would change the tensile residual stress at the spot center to compression.

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