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Citation	Transactions of JWRI. 2007, 36(2), p. 81-86
Version Type	VoR
URL	https://doi.org/10.18910/10451
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Note	

Transactions of JWRI, Vol. 36 (2007), No. 2

Residual Stress of Steels for Structure and Fillet Weld Zone after Laser Peening[†]

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Abstract

Laser peening is an innovative surface enhancement technology to introduce a compressive residual stress in metallic materials. Experimental results showed that laser peening was effective in preventing SCC and enhancing fatigue strength. However the effects of laser peening on steels for structure and their welded zone are not completely clarified.

In this paper, laser peening conditions for four grades of steels for structure were examined. Moreover residual stress of the fillet weld zone after laser peening was investigated by comparing it with that before laser peening. X-ray diffraction was used to measure the residual stress. Main results are summarized as follows. 1) Laser peening affects steel hardness up to the depth of 0.6mm. 2) Laser peening conditions for over 400kN/mm^2 grade steels were selected as 200 mJ laser pulse energy, 8 ns pulse duration, 0.8 mm spot diameter and 3600 pulse/cm^2 irradiation pulse density. 3) Laser peening can change tensile residual stress to large compressive residual stress in the welding zone. The nearer to the welding toe, the larger this effect by laser peening became.

KEY WORDS: (Laser Peening) (Residual Stress) (Fillet Weld) (Steel for Structures) (Vickers Hardness)

1. Introduction

Laser peening is an innovative surface enhancement technology to introduce a compressive residual stress in metallic materials[1)]. Fundamental Process of laser peening is summarized as follows (**Fig.1**).

When an intense laser pulse is focused on the material, the surface absorbs the laser energy and a submicron layer of the surface evaporates instantaneously. Water confines the evaporating material and the vapor is immediately ionized to form plasma by inverse bremsstrahlung. The plasma absorbs subsequent laser energy and generates a heat-sustained shock wave, which impinges on the material with an intensity of several gigapascals, far exceeding the yield strength of most metals[2)]. The shock wave loses energy as it propagates to create a permanent strain. After the shock wave propagation, the surface is elastically constrained to form a compressive residual stress on the surface[3)]. X-ray diffraction study showed that the compressive residual stress, nearly equal to the yield

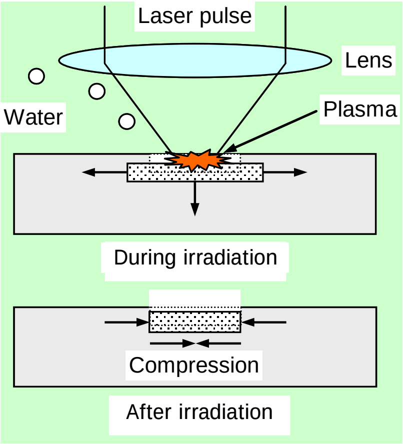

Fig. 1 Basic process of laser peening

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† Received on December 14, 2007

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Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

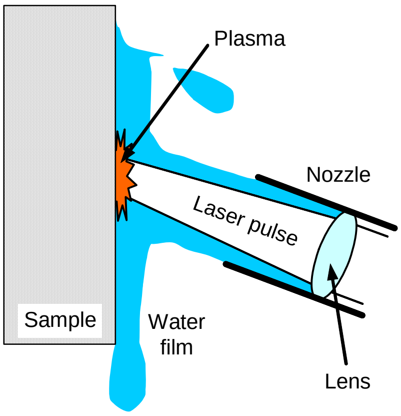


Fig.2 Laser peening process with water jet from nozzle

strength, was imparted to the surface of the material. Laser peening was effective to prevent the initiation and propagation of stress corrosion cracking (SCC). Taking advantage of the inertia-less process of laser peening over mechanical treatment, a remote-controlled process system has been developed and applied to nuclear power reactors as a preventive maintenance measure against SCC[4].

Laser peening changes tensile residual stress to compressive. So it seems that laser peening will be very effective in enhancing the fatigue strength, because tensile residual stress is one of the most important factors to reduce fatigue strength. Recent studies have revealed that laser peening dramatically improved the fatigue properties of austenitic stainless steel[5], aluminum alloys[6, 7] and titanium alloys[8], in spite of the increase in surface roughness.

But the effect of laser peening for "steels for structures", that are widely used for steel structures like bridges, buildings and so on, are not well clarified, much less the effect for their welded zones. If laser peening can impart compressive residual stress to the steels for structures and its welded zone, fatigue lives of the steel structures will be largely extended. Laser, which were used in this research, can be delivered by an optical fiber[9]. As shown in **Fig.2**, a type of laser peening process with water jet from a nozzle is already developed. So it seems that laser peening can be widely used in factories as well as in field sites.

In this study, laser peening conditions for four grades of steels for structures were examined. Moreover, residual stress of fillet weld zones after laser peening were investigated by comparing them to those before laser peening.

2. Laser peening condition for 490kN/mm^2 grade steel

To decide the laser peening conditions for the steels for structures, 12mm thickness of 490kN/mm^2 grade steels (SM490, σ_Y=400MPa, σ_U=556MPa) were peened with four conditions of laser peening and residual stresses of surfaces were measured by X-ray diffraction (XRD). Cr-Kα (17kV, 2.0mA) was used as the X-ray source and the $\sin^2\psi$ method was used.

The laser peening conditions are shown in **Table 1**. Irradiation frequency was 60Hz and irradiation area was 10mm x 10mm. It took about 1 minute to perform laser peening under this condition.

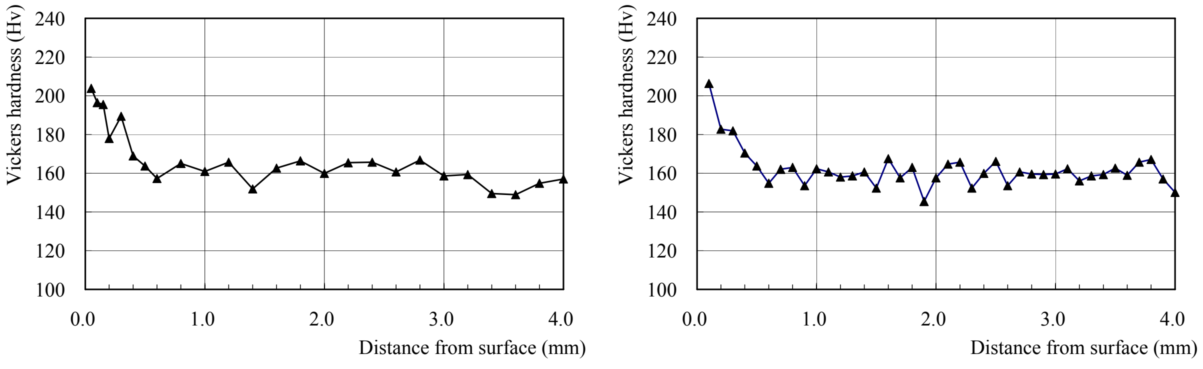
Results of residual stress measurement are shown in Table 1. σ_ξ and σ_η indicate a residual stress component in parallel and normal to the scanning direction of the laser beam. Values before ± show most provable values which are found by the $\sin^2\psi$ method and values after ± show confidence intervals (1σ) in table 1. It can be said that residual stress was measured accurately because the confidence intervals were smaller than 30MPa. Residual stress was compressive in all conditions. The values of compressive stress were in the same range except σ_ξ of No.3. There was trend that the values of σ_ξ are larger than the values of σ_η. This tendency was observed in research used other materials and more consideration will be needed.

Vickers hardness over the thickness was measured to study the depth of the effect of laser peening in each condition.

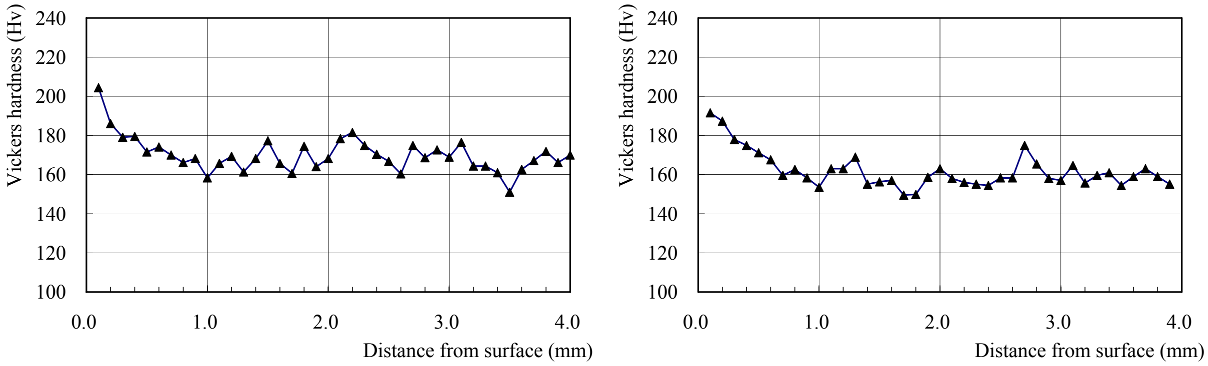
Results are shown in **Fig.3 (a) – (d)**. Test load was 1.96kN. The hardness values near the surface were about 200Hv and increased by about 40Hv compared to untreated areas for all laser conditions. The hardened area was depth of 0.6-1.0mm from the surface. So it can be said that laser peening affected the hardness of the steels for structure up to depth of 0.6mm for any laser conditions.

Table 1 Laser peening condition and residual stress measured by XRD

Specimen No.	Pulse energy (mJ)	Spot diameter (mm)	Irradiation Density (Pulse/cm^2)	Residual stress (MPa)	
				σ_ξ	σ_η
No.1	200	0.8	3,600	-237±5	-360±11
No.2	200	0.8	10,000	-231±5	-361±21
No.3	300	1.0	3,600	-161±12	-387±12
No.4	300	1.0	10,000	-240±10	-323±24



(a) No.1 (b) No.2



(c) No.3 (d) No.4

Fig.3 Results of Vickers hardness test

As described above, residual stress and Vickers hardness at the surface were not affected by the laser peening conditions in the case of the 490kN/mm^2 grade steel.

3. Effect of material strength of steels

To clarify the effect of material strength (yield stress and tensile stress) of the steels for structure on changes of residual stress by laser peening, four grades of steels were peened by laser and residual stress of the surface were measured by XRD. **Table 2** shows tensile test results and chemical compositions of the examined steels. The laser peening condition of No.1 in table 1, which is the smallest laser energy invested among four conditions, was used. Irradiation frequency was 60Hz and two spots of 10mm x 10mm area were irradiated in each steel. Residual stresses were measured by XRD on two different points in laser-peened area and on single point in unpeened area. The XRD conditions were same in section 2.

Results of residual stress measurement are shown in Table 3. Even in the unpeened area, small compressive residual stresses were imparted in all steels. It seems that these were imparted during the cooling process in roll forming. In the case of SM400, SM490 and HT780, large compressive residual stresses were imparted in laser-peened area. The material strength was not

Table 2 Tensile test results and chemical compositions of steels for structures

	Tensile test results				Chemical composition (%)											
	σ_Y	σ_U	δ	YR	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	Ceq
	(MPa)	(MPa)	(%)	(%)	$\times10^{-2}$			$\times10^{-3}$		$\times10^{-2}$				$\times10^{-3}$		$\times10^{-2}$
HT780	789	842	19	94	19	23	145	9	1	-	-	-	-	-	1	44
SM490	400	556	23	72	16	36	136	11	5	-	2	4	4	0	-	41
SM400	374	452	32	83	11	22	98	12	4	-	1	2	1	0	-	28
LY	91	265	56	34	0	1	16	13	4	-	-	-	-	-	Ti 40	3

Ceq=C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14

Table 3　Residual stress of steels for structures measured by XRD

	Unpeened area (MPa)		Leser-peened area Point ① (MPa)		Point ② (MPa)		Means (MPa)	
	σ_ξ	σ_η	σ_ξ	σ_η	σ_ξ	σ_η	σ_ξ	σ_η
HT780	-44±18	-35±30	-171±6	-304±11	-178±6	-321±6	-174±6	-312±8
SM490	-125±14	-169±17	-271±11	-417±12	-271±10	-459±6	-271±11	-438±9
SM400	-92±12	-69±14	-208±7	-335±11	-202±6	-340±9	-205±7	-338±10
LY	-72±22	-41±42	-81±19	-162±20	-79±18	-156±26	-80±18	-159±23

directly correlated with the values of residual stress. In the case of LY, the values of σ_η increase slightly from about 40 MPa to 160 MPa, but the values of σ_ξ were not changed. It can be said that the large compressive residual stress cannot be imparted in the steels, which have low material strength like LY, by this laser peening condition.

In any steels, the values of residual stress in two spots of laser-peened area agreed well. It seems that this indicates the high reliability of the laser peening process.

As described above, it can be said that material strength of the steels for structures did not affect the compressive residual stress imparted by laser peening in the case of over 400kN/mm^2 grade steels. And Laser peening conditions for over 400kN/mm^2 grade steel can be decided as the smallest laser power condition in this research (200 mJ laser pulse energy, 0.8 mm spot diameter and 3600 pulse/cm^2 irradiation pulse density). In this case, pulse duration was 8 ns, scanning speed of laser was 10mm/sec. And the peak power density was 50 TW/m^2, which generated plasma with the peak pressure of about 3.2 GPa.

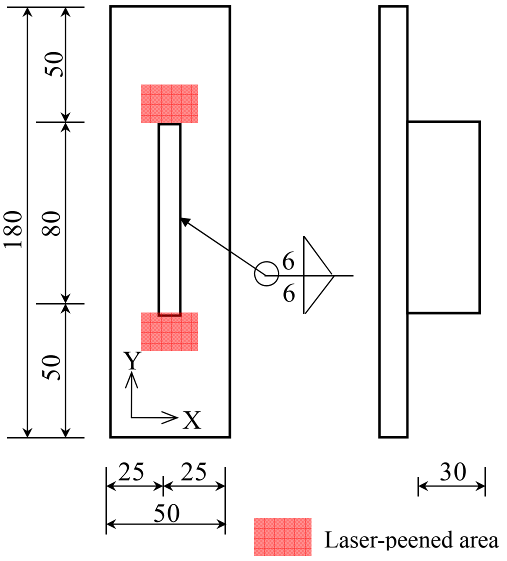


Fig.4　Specimen for residual stress measurement

4. Change of residual stress in welding toe

To clarify the effect of the change of residual stress in the welded zone by laser peening, welding toes of a rib-plate were peened by laser and residual stresses of surfaces were measured by XRD both before and after peening. As shown in **Fig.4**, a fillet-welded rib-plate specimen was prepared by welding a 9 mm thick rib (SM490, σ_Y=419MPa, σ_U=541MPa) to a 12 mm thick plate (SM490, σ_Y=380MPa, σ_U=561MPa) with a length of 180mm and a width of 50 mm. Carbon-dioxide (CO$_2$) gas shield welding was used with a JIS Z 3312

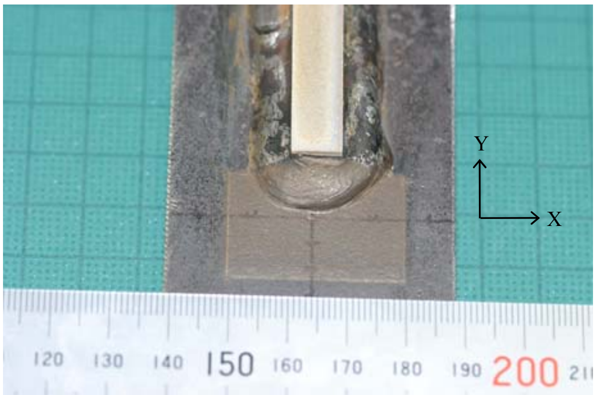


Fig5　Laser-peened toe of fillet weld

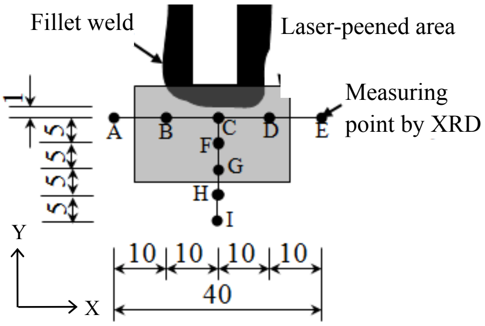
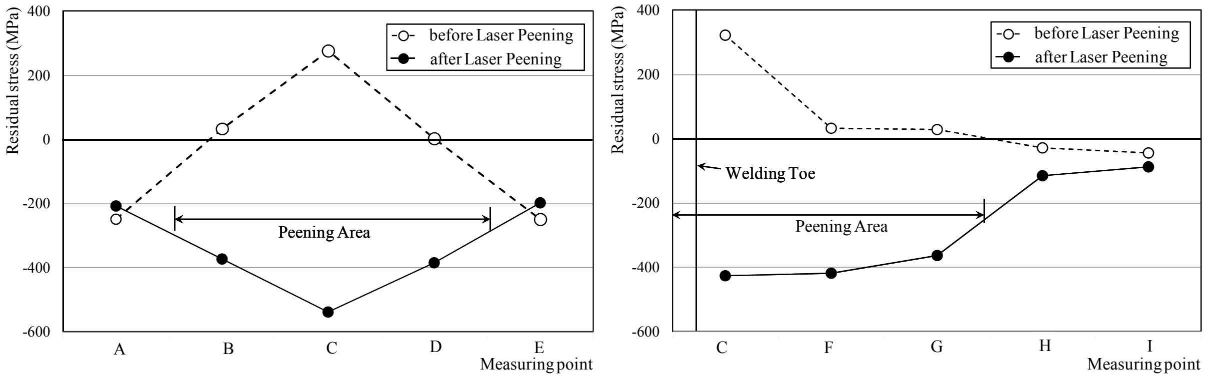
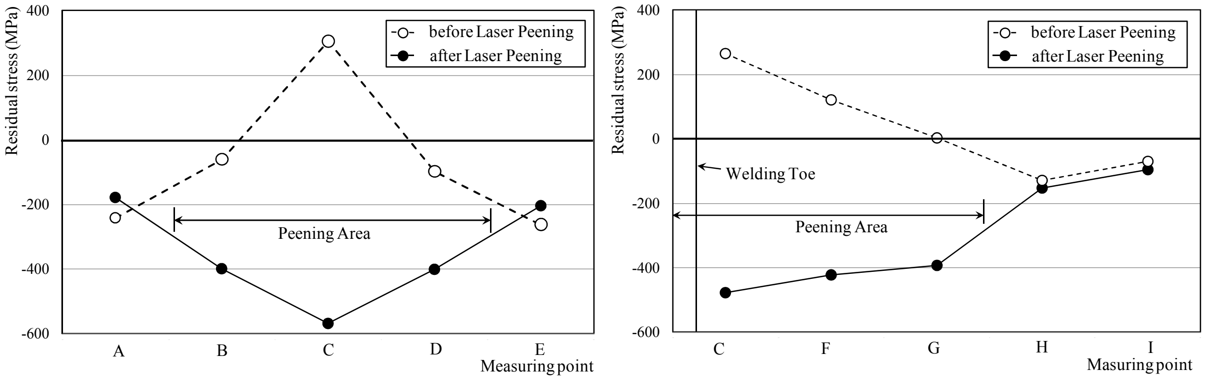


Fig.6　Measuring point by X-ray diffraction



(a) X-direction (b) Y-direction

Fig.7 Residual stress distribution of upper side welding toe (σ_y)



(a) X-direction (b) Y-direction

Fig.8 Residual stress distribution of lower side welding toe (σ_y)

YGW11 filler wire.

Laser-peened area is shown in **Fig.4** and **Fig.5**. Laser peening was performed to cover an area of 20 x 30 mm around the welding toe where stress concentration was evident. The laser peening condition, described in section 4, was used. Welding toes (the upper and lower in Fig.4) were irradiated. The rib-plate was cut by electrical discharge at a height of 8mm, because the rib-plate disturbed residual stress measurement of a Y-direction stress component (σ_y) by XRD.

Figure 6 shows measuring points of the residual stress in the fillet-welded rib-plate. The XRD conditions were the same as in section 2 and 3.

Residual stress distributions (σ_y) are shown in **Fig.7** and **Fig.8**. At unpeened points (A, E, H, I), residual stress did not change at all by laser peening. But at laser-peened points (B, C, D, F, G), residual stress changed from tensile stress to large compressive stress. The nearest point to the welding toe (C) changed more than the other laser peened points (B, D, F, G), and compressive residual stress of point C was nearly equal to or more than the yield stress. So it can be said that the nearer to the welding toe, the larger the effect to residual stress by laser peening became[9].

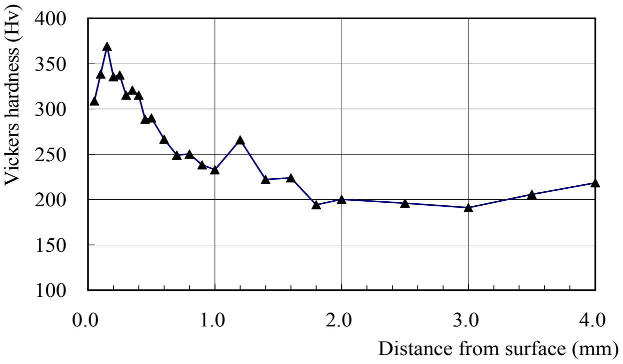


Fig.9 Vickers hardness distribution of welded toe

Results of Vickers hardness measurement over the thickness at point C are shown in **Fig.9**. Test load was 1.96kN. The hardness values near the surface were over 300Hv and increase about 100Hv compared to the unpeened area. The hardened area was at a depth of 1.5mm from surface. Hardness of the surface and affected thickness increased compared to those of the steel plate without laser peening. It seems that these are caused by both welding heat input and laser peening.

5. Conclusions

(1) Vickers hardness changed to a depth of 0.6 - 1.0 mm by laser peening. So it can be said that laser peening affects the hardness of the steels for structure up to the depth of 0.6mm.

(2) In the case of over 400kN/mm^2 grade steels, material strength of the steels for structure did not affect the compressive residual stress imparted by laser peening.

(3) Laser peening conditions for over 400kN/mm^2 grade steel were selected in our experiment as 200 mJ laser pulse energy, 8 ns pulse duration, 0.8 mm spot diameter and 3600 pulse/cm^2 irradiation pulse density.

(4) Laser peening can change the tensile residual stress to large compressive residual stress in the welding zone. The nearer to the welding toe, the larger this effect by laser peening became.

In this report, fatigue life of welded joint of the steels for structure was not discussed. Some recent research suggests that the effect of laser peening to fatigue life is large[10) - 12).] We will be reporting details at a later date.

Acknowledgments

This study was financially supported in part by the Grant-in-Aid for Young Scientists (B) (No.15760352) from the Ministry of Education, Culture, Sports, Science and Technology and by the research grant from the Japan Iron and Steel Federation. And steels were supplied by JFE R&D Corporation.

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