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# Fatigue Life Enhancement of Fillet and Butt Welded Joints after Laser Peening†

**SAKINO Yoshihiro*, SANO Yuji**, SUMIYA Rie ** and KIM You-Chul*****

## Abstract

*Laser peening which introduces compressive residual stresses on surfaces is effective in enhancing fatigue lives of welded components, because tensile residual stress due to welding is one of the most prominent factors reducing the fatigue lives. Structural steels are widely used for bridges, buildings, etc.; however, the effects of laser peening on the structural steels are not well established, especially on the welded zones.*

*In this study, the welded zones of a box-welded joint were treated by laser peening and the residual stress was examined. Moreover, fatigue lives were evaluated for box-welded joints and butt welded joints with and without laser peening. Results obtained are summarized as follows: (1) Laser peening resulted in a change in the residual stress from tensile to compressive around box welding zones of a fillet welded rib-plate. (2) Laser peening can dramatically extend the fatigue lives and increase the fatigue strength of fillet and butt welded joints.*

**KEY WORDS:** (Laser peening), (Fatigue life), (Residual stress), (Fillet weld), (Butt weld), (Steel for structures)

## 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

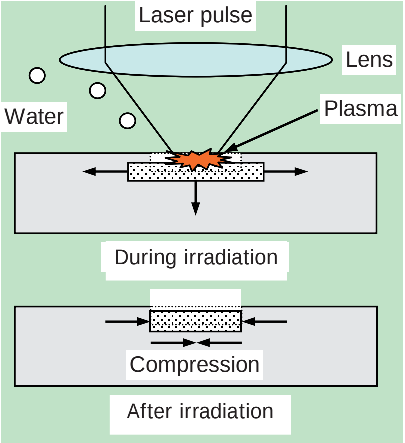

**Fig. 1** Basic process of laser peening

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strength, was imparted to the surface of the material.

Laser peening changes tensile residual stress to compressive. So it seems that laser peening will be very effective in enhancing the fatigue lives, because tensile residual stress is one of the most important factors which reduces fatigue lives. Recent studies have revealed that laser peening dramatically improved the fatigue properties of austenitic stainless steel[4], aluminum alloys[5] and titanium alloys[6], in spite of the increase in surface roughness due to direct irradiation of intense laser pulses. However, 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 their welded zone, fatigue lives of the steel structures will be largely extended.

The authors have studied irradiation conditions for laser peening of structural steels by measuring the residual stress and performing hardness tests.[7] Then, they also studied changes in the surface residual stress, the depth distribution of residual stress, the hardness distribution, and the surface roughness in four types of structural steel with different strengths.[7, 8]

In this study, residual stresses around welding toes were examined for the box welded zones pretreated by laser peening and compared with those before pretreatment. Moreover, the fatigue lives of the toes of the box welded zone of fillet welded joints and butt welded joints pretreated by laser peening were compared to untreated ones.

## 2. Change of residual stress in welding toe[8]

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.2**, a fillet-welded rib-plate specimen was prepared by welding a 9 mm thick rib (SM490, $\sigma_Y$=419MPa, $\sigma_U$=541MPa) to a 12 mm thick plate (SM490, $\sigma_Y$=380MPa, $\sigma_U$=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 YGW11 filler wire.

As shown in Fig.2 and **Fig.3**, laser peening was performed to cover the area of 20 x 30 mm around the welding toes of the box welding zone (the upper and lower in Fig.2) where stress concentration was evident. Laser peening conditions are 200 mJ laser pulse energy, 8 ns pulse duration, 0.8 mm spot diameter and 36 pulse/mm$^2$ irradiation pulse density. The scanning speed of the laser was 10mm/sec in this experiment with a laser oscillator of a 60 Hz pulse repetition rate. The corresponding peak power density was 50 TW/m$^2$, which generated plasma with a peak pressure of about 3.2 GPa. 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 ($\sigma_y$) by XRD. Cr-Kα (17kV, 2.0mA) was used as the X-ray source and the sin$^2$ψ method was used. **Figure 4** shows measuring points of the residual stress around the toe of the box welding zone.

Distributions of the residual stress component in the X-direction ($\sigma_x$) are shown in **Fig. 5**. Before laser peening, the residual stresses were tensile at the location of C, the nearest point to the welding toes, and about 0 at

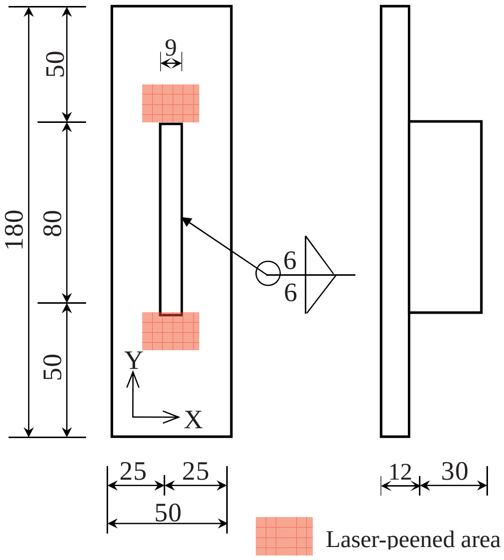


**Fig. 2** Specimen for residual stress measurement

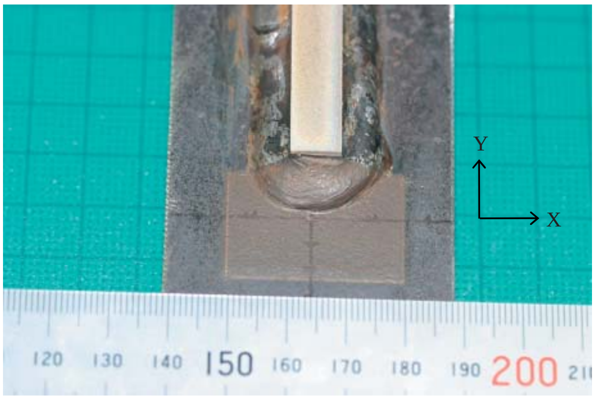


**Fig. 3** Laser peened toe of box welded joint

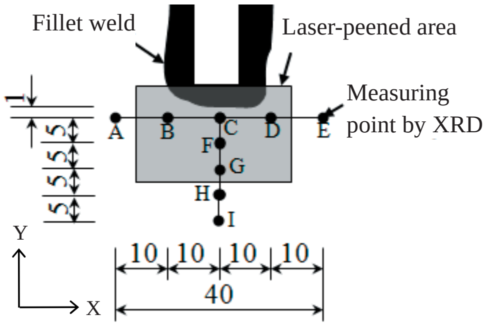
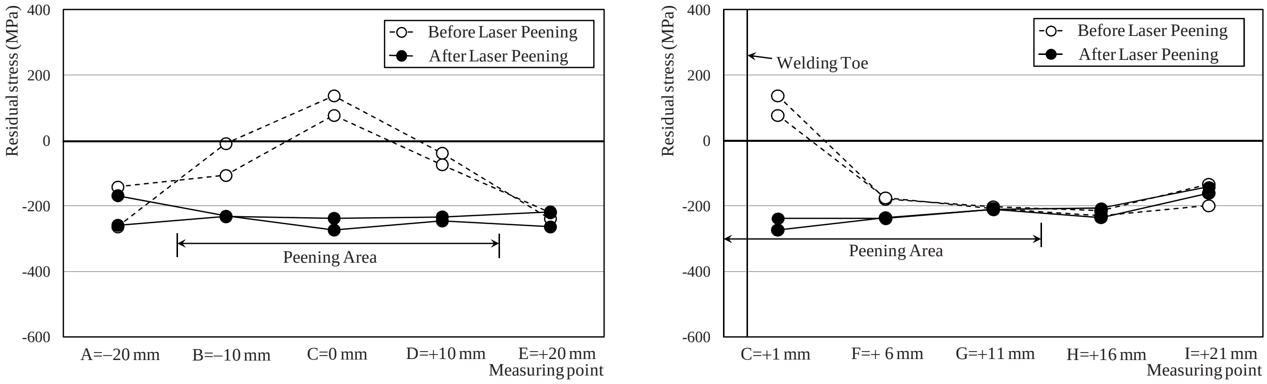
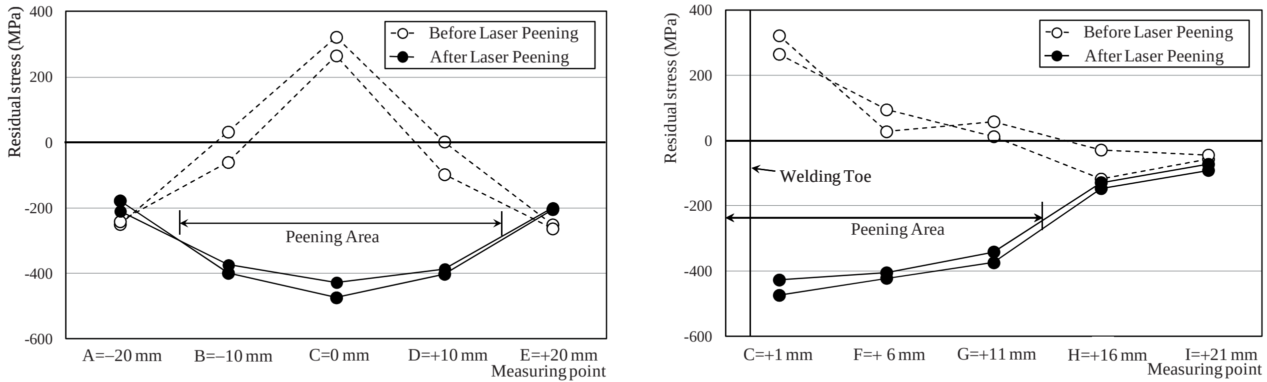


**Fig. 4** Measuring point by X-ray diffraction



(a) A-B-C-D-E line (b) C-F-G-H-I line

**Fig. 5** Residual stress distributions ($\sigma_x$)



(a) A-B-C-D-E line (b) C-F-G-H-I line

**Fig. 6** Residual stress distributions ($\sigma_y$)

B and D. The residual stresses were compressive and about -200 MPa at A, E, F, G, H and I. After laser peening, the residual stresses at all the locations were almost identical, namely about -200 MPa in compression, and did not depend on the residual stresses before laser peening.

Distributions in the Y-direction ($\sigma_y$) are shown in **Fig. 6**. Before laser peening, residual stresses were large tensile of about +300 MPa at the location of C. The residual stresses were about 0 at B, D, F, G, H and I, and compressive of about -200 MPa at A and E. Laser peening changed the residual stresses to compression at B, C, D, F and G, and the compression was slightly larger as approaching the welding toes. The changes in residual stress were most prominent at C, the nearest point to the welding toes, and the values of the base material were nearly equal to or greater than the yield stress of the base material.

It is supposed that this difference in the residual stress distributions was caused by the effect of constraint of the rib, but more study will be needed.

## 3. Fatigue lives of box welded joints[9)]

The fatigue lives of box welding zone of fillet welded joints were investigated with specimens shown in **Fig. 7**. Fillet welded rib-plates of SM490 mild steels were prepared by welding a 9 mm-thick rib ($\sigma_Y$ = 419 MPa, $\sigma_U$ = 541 MPa) to a 12 mm-thick base plate ($\sigma_Y$ = 382 MPa, $\sigma_U$ = 548 MPa) with a length of 430 mm and a width of 98 mm. The welding process and wire were the same as described in section 3. One end of the rib-plate was tapered with an angle of 45 deg and its box welded toe was ground into a concave shape by an

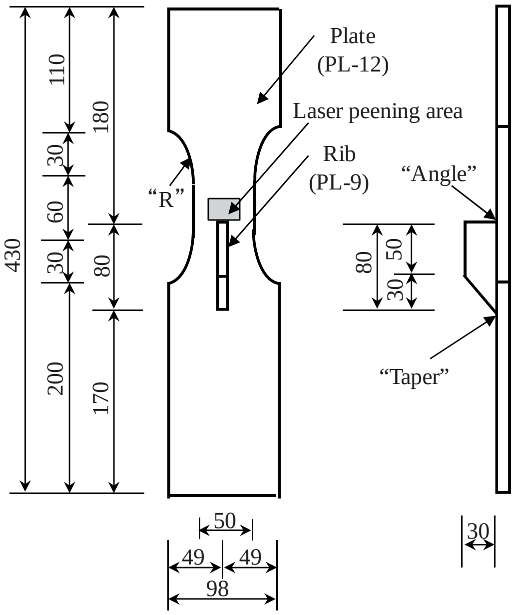


**Fig. 7** Fillet welded specimen for fatigue test.

**Table 1** Results of fatigue test

| Stress range (MPa) | With laser peening | | | | | Without laser peening | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number of stress cycle N (×$10^4$ cycles) | | | Initiation point | | Number of stress cycle N (×$10^4$ cycles) | | | Initiation point | |
| | No.1 | No.2 | Mean | No.1 | No.2 | No.1 | No.2 | Mean | No.1 | No.2 |
| 250 | >97.0 | >90.0 | >94.0 | Taper | Taper | 25.0 | 29.0 | 27.0 | Angle | Angle |
| 300 | >200 | >135 | >168 | − | Taper | 12.7 | 15.0 | 13.9 | Angle | Angle |
| 350 | >46.7 | >35.7 | >41.4 | Taper | R | 1.9 | 4.2 | 3.1 | Angle | Angle |
| 400 | 12.3 | 16.5 | 14.4 | Angle | Angle | 2.7 | 2.8 | 2.7 | Angle | Angle |

electric grinder and a pencil grinder. This end of the fillet welded joint was labeled “Taper.” Another end was left as welded and labeled “Angle.” The width of the base plate was narrowed from 98 mm to 50 mm around “Angle.” The nominal stress range of the toe in “Angle” was twice as much as that in “Taper.”

As shown in Fig. 7, laser peening was performed to cover an area of 20 mm × 30 mm around the toe in “Angle,” where stress concentration was evident. The same laser peening conditions as section 2 were used here.

Fatigue lives were studied through a series of fatigue tests under pulsating loading for the fatigue specimens with and without laser peening. The loading stress ranges, considering the narrowed width of the base plate, were 250, 300, 350 and 400 MPa, and the stress ratio was 0. Two specimens, No.1 and No.2, were examined in each stress range.

The fracture initiation points of the specimens are shown in **Table 1**, and typical specimens after the fatigue tests are shown in **Fig. 8**. As expected, the fatigue crack initiated from the toe in “Angle” for all the specimens without laser peening. However, cracks initiated from unexpected points in specimens with laser peening under stress ranges of 250, 300 and 350 MPa, except the 300 MPa/No.1 specimen. This specimen did not fracture until 2 × $10^6$ loading cycles, the maximum available fatigue cycles in this test. In specimens with laser peening, fatigue cracks initiated from the toe in “Taper” or the border of the parallel part and the fillet part (labeled as "R" in Fig. 7), even though the stress range and stress concentration at the toe in “Angle” were larger than those at the crack initiation points. In the case of the 400 MPa stress range, fatigue cracks initiated from the toes in “Angle,” the same position as in the specimens without laser peening.

The fatigue life of each specimen is shown in Table 1 and illustrated in **Fig. 9**. The vertical axes in Fig. 9 are normalized so that the average fatigue lives of two specimens without laser peening would be unity for each stress range. The numerals in Fig. 9 are the stress cycles to fracture counted in the unit of $10^4$. The box-welded toes in “Taper” of the 250 MPa specimens with laser peening were ground roughly compared with the other specimens. Consequently, the fatigue lives of the 250 MPa specimens were shorter than those of the 300 MPa. The fatigue life at a lower stress range should be longer than that of a higher under the same conditions other than the stress range. Therefore in Fig. 9 (a), the same lives as the 300 MPa specimens with laser peening are assumed for the 250 MPa specimens.

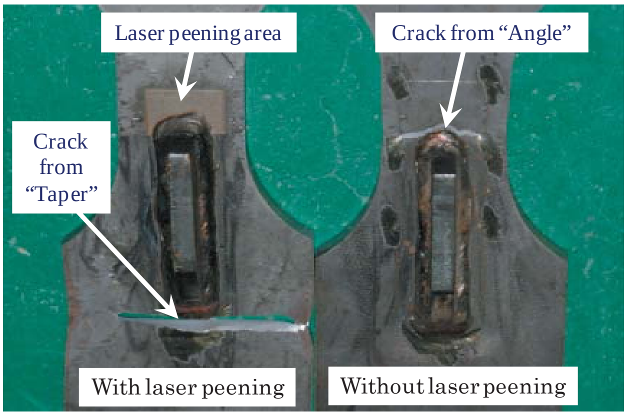


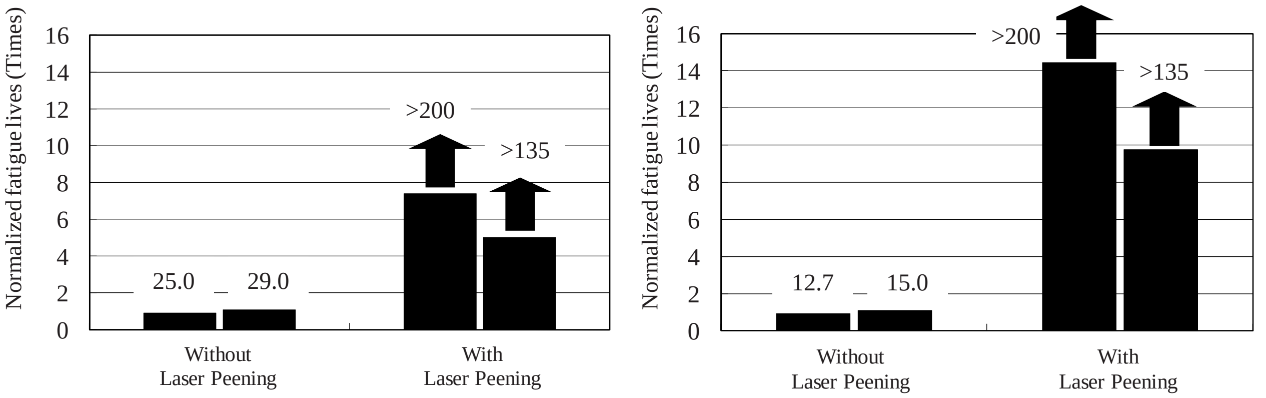
**Fig. 8** Specimens after fatigue tests

In this study, the fatigue lives could not be accurately determined for the specimens with laser peening. This is because the fatigue cracks of most specimens with laser peening did not initiate from "Angle" but initiated from "Taper." However, the fatigue lives of the fillet welded joints were surely extended by laser peening 5 times or more under a stress range of 250 MPa, 10 times or more under 300 MPa, 12 times or more under 350 MPa and about 5 times under 400 MPa. Thus, the overall results show that laser peening can dramatically extend the fatigue lives of the box-welded joints.

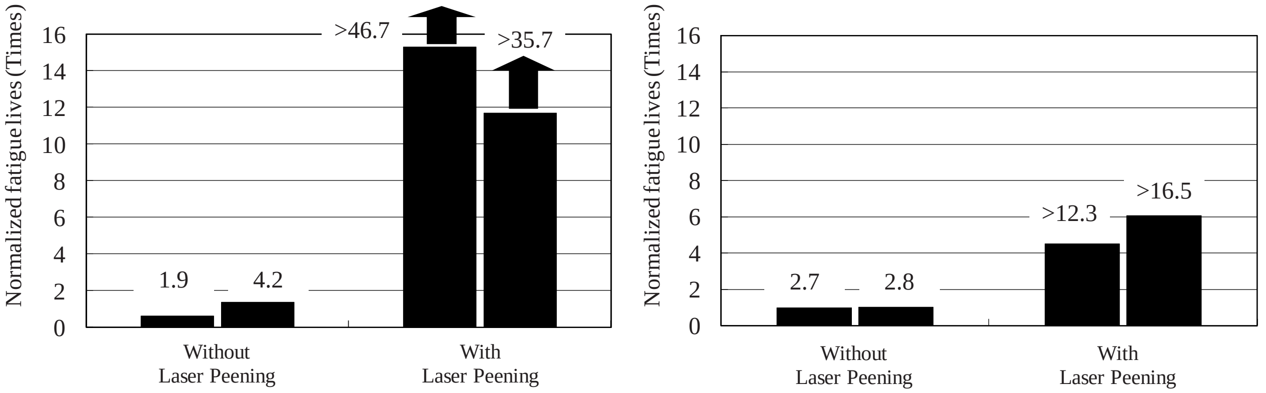
## 4. Fatigue lives of butt welded joints[9)]

The fatigue lives of the toes of butt-welded joints were also investigated. A diagram of the specimens used for the fatigue test is shown in **Fig. 10**. Two plates of an SM490 mild steel ($\sigma_Y$ = 365 MPa, $\sigma_U$ = 524 MPa) were welded with a V groove from one-side. A copper backing bar was used during welding and removed afterward. Geometric stress concentration does not exist in the back side of the specimens. The welding process and wire were the same as described in section 2.

As shown in Fig. 10, laser peening was performed for areas of 15 mm × 20 mm covering the welding bead on the both (front and back) sides. The same laser



(a) Δσ=250MPa (b) Δσ=300MPa



(c) Δσ=350MPa (d) Δσ=400MPa

**Fig. 9** Comparison of fatigue lives at the point of "Angle"

peening conditions as section 2 were also used here. In a pilot test with laser peening only on the front side, fatigue cracks initiated from the back side without any geometric stress concentration.

Fatigue lives were studied through a series of fatigue tests under pulsating loading for the specimens. The loading stress ranges were 175, 200, 250, 300 and 350 MPa for specimens without laser peening, and 250, 300 and 350 MPa for specimens with laser peening. The stress ratio was 0 and three or four specimens were examined in each stress range. The fatigue cracks initiated from the welding toes on the front side in all the specimens. The resulting S-N diagram is shown in **Fig. 11**.

In case of the specimens without laser peening under the stress range of 175MPa, the fatigue lives exceeded $10^7$ cycles that is the maximum available cycles in this test series. The fatigue lives of two specimens under the stress range of 200 MPa also exceeded $10^7$ cycle and the other two specimens fractured within $10^6$ cycles. From these results, the fatigue strength at $10^7$ cycles of the specimens without laser peening would be 175 MPa. All specimens under the stress ranges of 250, 300 and 350 MPa also fractured within $10^6$ cycles.

In case of the specimens with laser peening, the fatigue lives exceeded $10^7$ cycles under the stress ranges of 250 and 300 MPa. All specimens under the stress

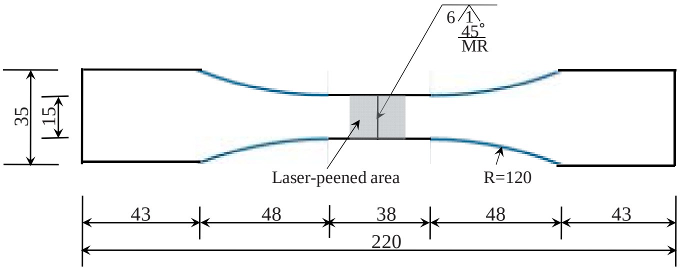


**Fig. 10** Butt-welded specimen for fatigue test.

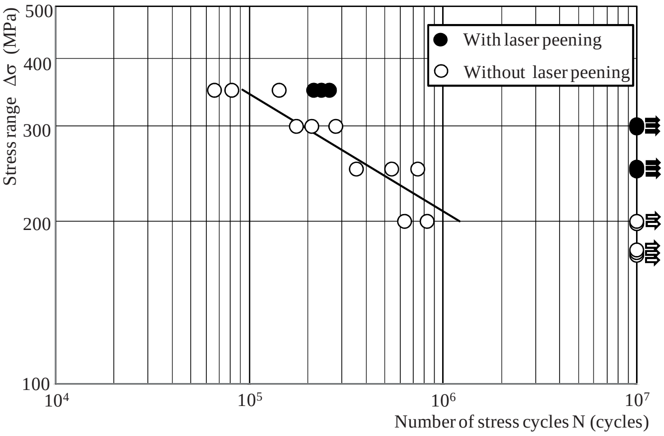


**Fig. 11** S - N diagram.

range of 350 MPa, which is nearly equal to the yield stress of the base metal, fractured within $10^6$ cycles, however, the fatigue lives of the specimens with laser peening were two times longer or more compared to the specimens without laser peening. From these results, fatigue strength at $10^7$ cycles of the specimens with laser peening would be 300 MPa and 1.7 times greater compared to the specimens without laser peening.

Thus, the overall results show that laser peening can also dramatically extend the fatigue lives and increase the fatigue strength of the fillet welded joints.

## 5. Conclusions

(1) Laser peening resulted in a change in the residual stress from tensile to compressive around box welding zones of a fillet welded rib-plate. The degree of this change showed a maximum at the nearest point to the welding toe. In the normal direction to the rib-plate, the level of the compression was almost identical regardless of the initial residual stress before laser peening. In the parallel direction, however, the compressive residual stress after laser peening was slightly larger as approaching the welding toe.

(2) The fatigue lives of the fillet welded joints with laser peening were at least 5 times greater than those without laser peening under the stress range of 250 MPa, 10 times or more under 300 MPa, 12 times or more under 350 MPa and about 5 times under 400 MPa. Fatigue strength at $10^7$ cycles of the butt-welded joints with laser peening was 300 MPa and 1.5 times greater compared to the specimens without laser peening. Fatigue tests revealed that laser peening dramatically extends the fatigue life and increase the fatigue strength of welded joints.

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