Effect of Laser Peening on Improving Fatigue Strength of Welded Rib of High-Strength Steel

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1. Introduction

In recent times, increase in the size of steel structures has led to an increased demand for lighter steel structure; this demand has been satisfied through the use of high-strength steel with tensile strengths exceeding 570 MPa in welded structures such as penstocks and long-span bridges. Compared to mild steel, high-strength steels not only facilitate the building of lighter structures through the reduction in plate thickness, but also are easy to weld, reduce man-hours required for welding and save materials[1]. Therefore, high-strength steel plays a significant role in large structures. However, high stress concentration at the toe or other welded zones of the structure often results in fatigue cracking. This stress concentration is known to significantly depend on shape but not the strength of the base metal. This indicates that although tensile strength of high-strength steel is higher than that of mild steel, the fatigue strength of a welded structure employing high-strength steel does not differ greatly from that of a welded structure of mild steel. Thus, the fatigue strength at the welded part substantially reduces the advantage of using high-strength steel.

Of the various methods employed for improving the fatigue strength of a welded zone, the authors have focused on laser peening. In this process, a laser with a pulse width of several to tens of nanoseconds is used to irradiate a material placed in a transparent medium (such as water) to generate high-pressure plasma, and the strength of the material surface is improved owing to the impact force by the plasma[2]. **Figure 1** shows underwater irradiation of laser peening. By generating large compressive residual stress on the surface of a material, laser peening is known to effectively prevent stress corrosion cracking[3]. In fact, this method is used to prevent stress corrosion cracking in the core shroud of a boiling water reactor and the inner face of a tube stand in a neutron measurement system that runs through the lower sphere of the reactor vessel in a pressurized water reactor. Laser peening enables reliable processing as it can control the irradiation conditions for each pulse. The computerized equipment can precisely control the location and focus of the irradiating beam, and the process offers excellent adaptability to complicated and narrow zone as it involves a small irradiation diameter[3]. It

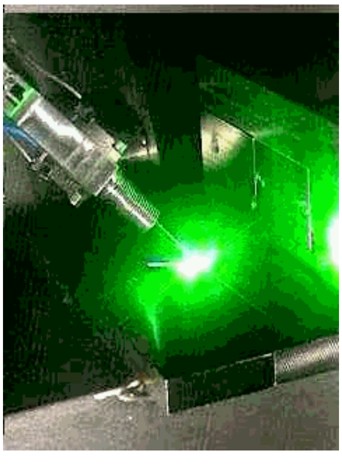


Fig. 1 Underwater laser peening

has also been reported that this laser peening method enables deeper effect compared to peening techniques such as shot peening4). In order to improve fatigue strength through the generation of compressive residual stress, fatigue tests are often performed on austenitic stainless steel5), aluminum alloys6),7), and titanium alloys8). However, laser peening of neither structural steel nor its welded zones has been investigated yet; structural steel is used in large structures such as bridges and buildings.

Hence, the laser peening condition of structural steel has been clarified as a part of the basic research for the application of laser peening to the welded zones of large structures such as bridges where fatigue cracks have been a serious issue9),10). Further, it has been confirmed that laser peening generates compressive residual stress in the welded zones of structural steel (SM 490), and thus, substantially extends the fatigue life 10)-12). However, the effect of laser peening on the welded zones of high-strength steel under the same laser conditions as applied to structural steel (SM 490) is not clear.

This study targets HT780 as a high-strength steel in order to clarify whether laser peening generates compressive residual stress on the surface of HT780, and whether such stress would account for prolonged fatigue life in the welded zones of HT780.

2. Basic Process of Laser Peening

Figure 2 shows a schematic diagram of the mechanism by which laser peening generates residual stress3). Irradiation by a strong laser pulse, exceeding the abrasion threshold, on a material submerged in water converts the material surface to plasma and generates high pressure plasma on the surface. Under water, the inertia of the water prevents the plasma from expanding, which consequently concentrates the laser energy in a small area. As a result, the plasma pressure becomes 10-100 times larger than in the atmosphere and reaches GPa levels13). This pressure generates a shock wave that passes in the material. The shockwave causes plastic deformation of the material, and the restraint from the surrounding non-deformed spots generates compressive residual stress on the surface14). The residual stress can be generated evenly and without scattering by continuously irradiating the object by moving the laser beam.

The laser used in this study was a commercially available small Nd:YAG, with a

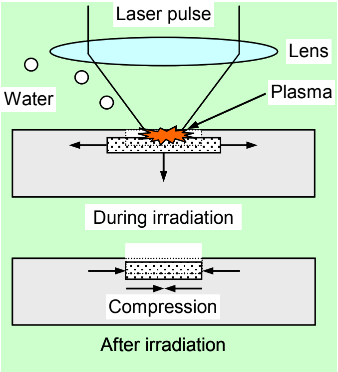


Fig.2 Mechanism for residual stress improvement using laser irradiation

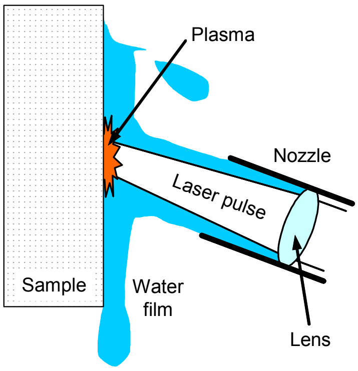


Fig.3 Laser peening accompanied by water flow from nozzle

small pulse energy that allowed an optical fiber to be used for the transmission line[15]. The water film was approximately 0.1 mm thick; this was necessary for suppressing the plasma expansion. In the case of use in welded zones of bridges or other structures, this was achieved by irradiating with the laser while injecting water from the nozzle, as shown in **Fig. 3**. Thus, laser peening can be used in factories as well as on site.

3. Change of Residual Stress by Laser Peening

The residual stresses of the laser-peened base metal and the laser-peened boxing toe of the welded rib plate of high-strength steel (HT780) was measured to determine whether laser peening generated compressive residual stress on the surface. The measured values were compared with the residual stress on an unpeened specimen in order to identify the change of residual stress by laser peening.

3.1 Residual stress in parent metal

For two different production rots of the 9 mm thick high-strength steel (HT780-1 and HT780-2), the surface residual stresses were measured at the laser-peened spots and at the unpeened spots. **Tables 1** and **2** list the mechanical properties and chemical compositions of the two steels.

Laser peening of the high-strength steels are performed under the same conditions as those applied for the peening of SM490 steel. Pulse energy is 200 mJ, spot diameter is 0.8 mm, and irradiation density is 3600 pulse/cm^2 [9]. The pitch of the pulse laser was 1/60 mm, and the stage with the specimen placed on it was moved. After the stage was moved by 10 mm, the process was reversed in order to have a line 1/60 mm below the irradiated area. The repetition of this process resulted in the irradiation of an area of 10 x 10 mm. The residual stress was measured by the X-ray diffraction (XRD, the $\sin^2\psi$ method) obtained using Cr-Kα (17 kV, 2.0 mA) as the X-ray source.

Table 1 Mechanical properties

	Mechanical properties			
	σ_Y (MPa)	σ_U (MPa)	δ (%)	YR (%)
HT780-1	789	842	19	94
HT780-2	804	823	21	95
Welding wire*	710	830	24	-

*: catalogue value

Table 2 Chemical composition

	Chemical composition (%)											
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	Ceq
	$\times 10^{-2}$		$\times 10^{-3}$		$\times 10^{-2}$			$\times 10^{-3}$				$\times 10^{-2}$
HT780-1	19	23	145	9	1	-	-	-	-	-	1	44
HT780-2	15	36	120	12	1	1	1	10	12	0	1	42
Welding wire*	8	38	125	9	11	-	222	-	63	-	-	-

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

Table 3 Results of residual stress measurement

	① without Laser peening		② with Laser peening		Change by Laser peening (②−①)	
	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
HT780-1	-44±18	-35±30	-174±6	-312±8	-131	-278
HT780-2	-6±13	-70±7	-191±3	-330±6	-185	-260

Table 3 lists the measurement results, where the values are the mean of the two spots. σ_x represents the residual stress component in the direction of the stage movement, while σ_y is the component perpendicular to this direction.

In Table 3, the most probable values calculated through the $\sin^2\psi$ method and with confidence intervals (1σ) are listed after the ± symbol. The confidence interval has a ±30 MPa maximum but is mostly around ±10 MPa. The spots that were not laser peened generated a compressive residual stress around −6 to −70 MPa for σ_x and σ_y, respectively. This stress was probably generated during the cooling process of the manufacturing process for the steel plate. As for the laser peened spots, significant compressive residual stress around −170 to −190 MPa was generated at σ_x, and −300 to −330 MPa at σ_y. Comparing the residual stress components σ_x and σ_y, the former tends to result in greater compressive residual stress. The phenomenon also seen in other materials during laser peening needs further investigation. The variation between the laser peened and unpeened spots is around 150 MPa at σ_x and about 270 MPa at σ_y, showing a significant change in residual stress towards the compressed side. These values confirm that the base metal in high-strength steel generates large compressive residual stress on the surface when peening conditions employed for SM490 are applied

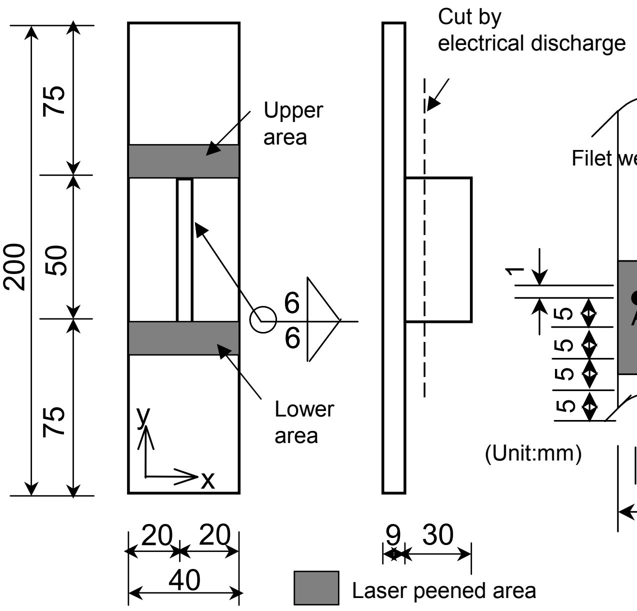


Fig.4 Specimen for residual stress measurement

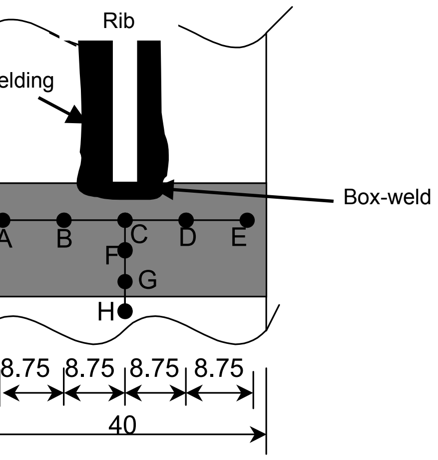


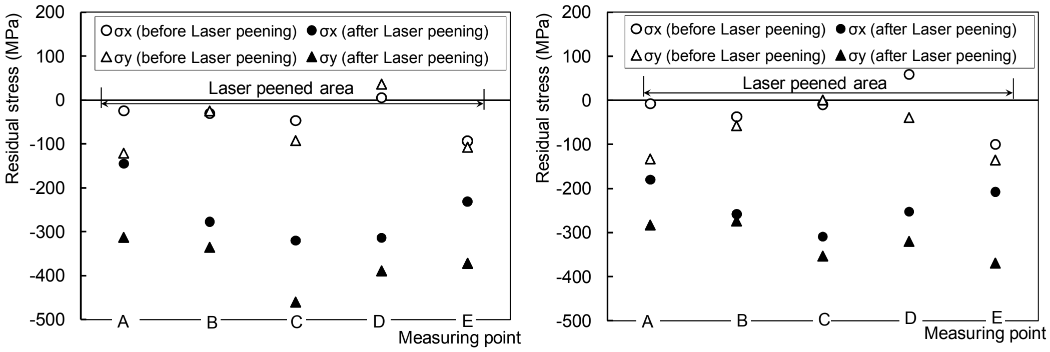
Fig.5 Measuring points of XRD

for the high-strength steel.

3.2 Residual stress in boxing toe

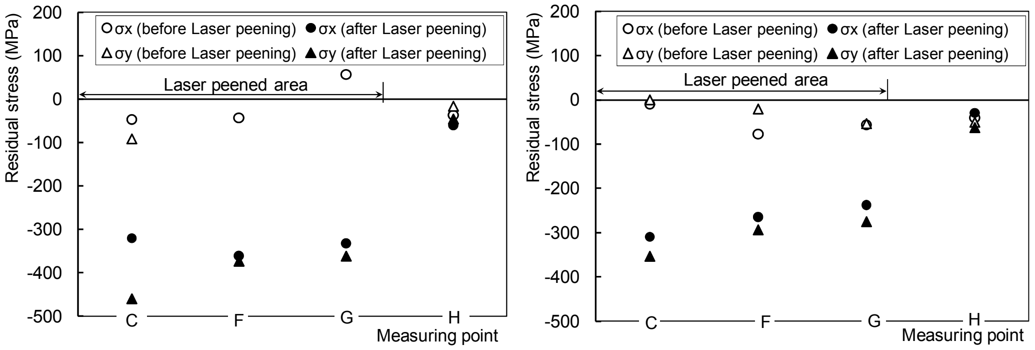
Figure 4 shows the shape and dimensions of the specimen, in which an all-round fillet (leg length: 6 mm) is welded to a 9 mm thick steel plate HT780-2, along with a 6 mm thick steel plate used as a rib. The 6 mm thick steel plate is obtained by reducing the thickness of HT780-2. CO_2 arc welding was employed and solid wire for the 780 MPa class steel was used as the welding material. Table 3 lists the catalogue values for the mechanical properties and chemical composition of the wire. 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 (σy) by XRD.

First, the residual stresses near the upper and lower boxing toes were measured. Then an area of 40 x 20 mm around the boxing toes was laser-peened and residual stresses at the same positions were measured. **Figure 5** shows points A-H, the positions where residual stresses were measured. Note that the conditions for irradiation and other factors are the same as in the case of the base metal, and the direction of moving the stage at irradiation is indicated in x in Fig. 4. **Figures 6** and **7** show the measurement results. σ_x is the residual stress component in the x direction (right angle to the rib), while σ_y is the residual stress component in the y direction (parallel to the rib). Before laser peening (indicated in ○ and △), a compressive residual stress of around 100 MPa was measured at points A and E, which are close to the edges of the specimen, while the



(a) Upper area (b) Lower area

Fig.6 Results of residual stress measurement (A, B, C, D, E)



(a) Upper area (b) Lower area

Fig.7 Results of residual stress measurement (C, F, G, H) stress was measured to be 0 MPa at other points. After laser peening (indicated by ● and ▲), no change in residual stress was seen at point H (the unpeened point), whereas large compressive residual stresses between −150 and −450 MPa were measured at the laser-peened points (A-G). Further, the closer a point is to the weld toe, the greater is the change in the compressive residual stress. In particular, point C, which is closest to the toe where fatigue cracking is initiated, shows the largest change in residual stresses following laser peening. It is therefore estimated that significant compressive residual stress is also generated near the boxing toe.

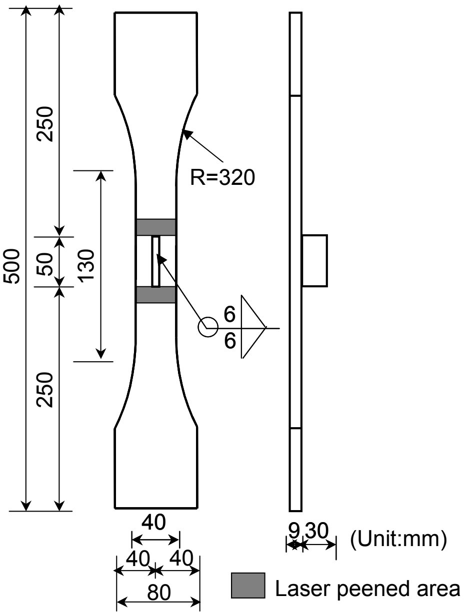


Fig.8 Specimen for fatigue test

4. Effect of Laser Peening on Fatigue Life

Fatigue tests were performed on laser-peened and unpeened specimens for a quantitative investigation to determine whether fatigue life in the boxing toe of high-strength steel prolonged by laser peening.

4.1 Experiment overview

Using the 300 kN uniaxial fatigue testing machine, a fatigue test was performed in constant stress ranges for the unpeened specimen (hereafter, called NP) and the laser-peened specimen (hereafter, called LP).

Figure 8 shows the shape and dimensions of the specimen in which an all-round fillet (leg length: 6 mm) is welded to a 9 mm thick plate, along with a 6 mm thick steel plate used as a rib. The steel material and welding conditions and materials are as mentioned in Section 3.2. The conditions, positions, and the laser-peened area are also the same as mentioned in Section 3.2.

Figure 9 shows the specimen shape and the laser-peening location. For the stress range to be loaded, there are three NPs at 200 MPa, three at 250 MPa, two each at 300, 350, 400, 450, 500, 550, and 600 MPa, making a total of 20 specimens; there are two LPs each at 300, 350, 400, 450, 500, and 600 MPa, one at 550 MPa, making a total of 13

Fig.9 Photograph of a box-welded rib specimen and its laser-peened area

specimens. The stress ratio was 0, and the censored limit was set at 10^7 times.

4.2 Experiment results

Figure 10 shows the S–N diagram obtained from the experiment. The arrows in the figure indicate that the number of censored limits of fatigue life is 10^7 times. The following sections will describe the experimental results in terms of crack–initiation positions, fatigue limit, and fatigue life.

4.2.1 Fatigue crack initiation position

Figure 11 shows photographs of the rupture surfaces. The mark ● in the figure represents the crack–initiation position, while the arrows show the direction in which cracking propagate. In the case of all NPs, crack initiation occurred at the boxing toe, where stress concentration exists. In the case of LPs exceeding 450 MPa, crack initiation occurred at the boxing toe as a result of stress concentration. However, in the stress range between 350 and 400 MPa, cracks were initiated at unpeened back side of the boxing toe, where stress concentration does not exist, instead of at the laser–peened toe.

The experiment revealed that the application of laser peening to the boxing toe accounts for the changes in the crack initiation positions owing to the differences in the stress ranges, and cracks initiate from the back side in relatively small stress ranges.

4.2.2 Fatigue limit

Three NPs in the 200 MPa stress range and one out of three in the 250 MPa range reached the censor limit of 10^7 times; the remaining two NPs in the 250 MPa range fractured at around 7 × 10^5 times and 26 × 10^5 times. This indicates that the fatigue limit of an unpeened specimen is 200 MPa.

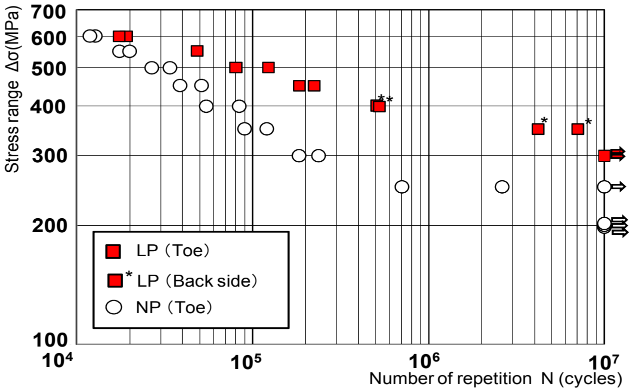


Fig.10 S–N diagram

(a) NP
(All stress ranges)

(b) LP
(Δσ = 350 and 400 MPa)

(c) LP
(Δσ = 450 – 600MPa)

Fig.11 Fracture surface

On the other hand, two LPs reached the censor limit of 10^7 times in the 300 MPa stress range and fractured after around 42×10^5 times and 7×10^6 times in the 350-MPa range. Therefore, the fatigue limit of the laser-peened specimen is 300 MPa. Further, cracks did not initiate from the toe but from the back side in the 350-400MPa stress range, illustrating the possibility that the fatigue limit of a laser-peened toe is 350 MPa or more.

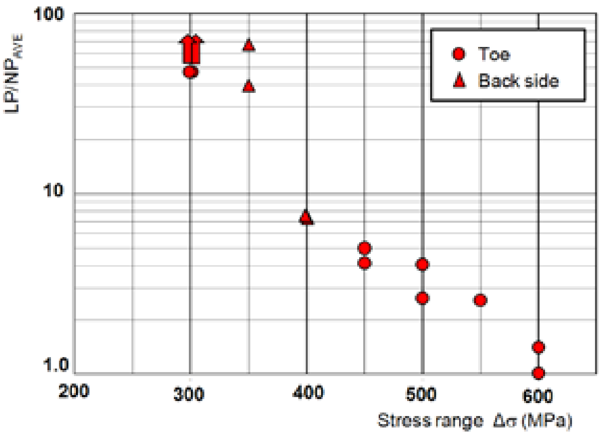


Fig.12 Comparison between NP and LP

Thus, the fatigue limit of the boxing toe in the high-strength steel increased from a stress range of 200 MPa to at least 300 MPa, i.e., by at least 1.5 times, as a result of laser peening.

4.2.3 Fatigue life

Figure 12 shows a comparison between the fatigue lives of NPs and LPs in each stress range. The vertical axis represents how many times the fatigue life of each LP is longer when the average fatigue life of two NPs in each stress range NP_{AVE} is set to 1. The arrows in the figure show that the fatigue life exceeded 10^7 times. The fatigue life was 1-1.5 times greater in the extremely high stress range of 600 MPa, indicating the reduced effect of laser peening. However, the fatigue life improved by more than 2.5 times in the 550-500 MPa range. In addition, the smaller the stress range is, the more significant is the improvement in the fatigue life, indicating that a fatigue life is at least 50 times greater in the 300 MPa stress range.

These results confirmed that laser peening of the boxing toe in high-strength steel does not improve the fatigue life in the 600 MPa stress range while it prolonged the fatigue life by approximately 2.5-50 times or more in the 300-550 MPa stress range. This remarkably extended the fatigue life of the boxing toe. It was further revealed that the smaller the stress range, the greater was the improvement in the fatigue life.

5. Conclusions

(1) Large compressive residual stress was generated on the base metal surface of the high-strength steel (HT780) under the peening conditions employed for SM490.

(2) Laser peening generated significant compressive residual stress at the boxing toe of the high-strength steel, where fatigue cracking is initiated.

(3) In the laser-peened boxing toe specimen of the high-strength steel, the initiated cracks varied depended on the stress range. For small stress ranges, cracks were initiated from the back side of the toe where no stress concentration was observed.

(4) The fatigue limit of the boxing toe of the high-strength steel was improved by at

least 1.5 times as a result of laser peening.

(5) The smaller the stress range, the greater was the improvement of the fatigue life of the high-strength steel boxing by laser peening. The fatigue life in the stress range between 300 and 550 MPa was prolonged by approximately 2.5- 50 times or more compared to the unpeened specimen.

Taking these points into consideration, it was concluded that laser peening of the boxing toe of the high-strength steel (HT780) generated significant compressive residual stress, which remarkably extended the fatigue life of this part[16].

Acknowledgement

This study was supported by JFE 21st Century Foundation "FY 2008 University Research Aid (Technical Research)." We were assisted in our work by Mr. Kenichi Yoshikawa, a graduate student of Osaka University and in the laser peening experiments by Dr. Yuji Sano, the executive advisory engineer for Toshiba Corporation. We would like to express our deepest gratitude to these individuals.

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