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

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Laser peening can introduce compressive residual stress to the surface and, therefore, is effective in enhancing the fatigue strength. This study targets 780 MPa grade high-strength steel (HT780) 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. As a result, large and deep compressive residual stress was generated on the base metal surface and at the boxing toe of HT780 under the peening conditions employed for 490 MPa grade steel. The smaller the applied stress range, the greater was the improvement of the fatigue life of the high-strength steel boxing toe by laser peening.

Key Words: Laser peening, High-strength steel, Fatigue strength, Box welded joint, Residual stress

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 reduce man-hours required for welding and save materials. 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 on 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 peening¹⁾. Laser peening is effective for preventing the initiation and propagation of stress corrosion cracking (SCC) and has been

applied to operating nuclear power reactors²⁾.

Recent studies have revealed that laser peening dramatically improves the fatigue properties of austenitic stainless steels³⁾, aluminum alloys⁴⁾, and titanium alloys⁵⁾. However, there is no open literature on the application of laser peening to huge structures such as bridges, other than the work of the authors. The fatigue life of bridges is decreasing significantly because of heavy traffic⁶⁾, and thus, it is necessary to reduce the welding residual stresses in bridge members. However, stress relief heat treatments⁷⁾ are not applicable to such big structures. Therefore, measures for reducing welding residual stresses in large welded structures that do not deteriorate the strength of the welded members are wanted. Laser peening is considered to be one of the most promising processes.

The authors studied laser peening conditions for structural steels by measuring the residual stress and performing hardness tests⁸⁾. 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 and in the welded zone⁹⁾. Moreover, it is clarified that the fatigue life of the welded joints is substantially extended by laser peening^{10), 11)} and the generation of compressive residual stress by laser peening is the major factor improving the fatigue life¹²⁾.

This study targets high-strength steel (HT780) 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. 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 HT780 were measured to determine whether laser peening generated

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compressive residual stresses on the surface. The measured values were compared with the residual stresses on an unpeened specimen in order to identify the change of residual stresses by laser peening.

3. Residual stress in base metal

For two different production lots 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 HT780s was performed under the same conditions as those applied for the peening of 490 MPa grade steel (SM490). Pulse energy is 200 mJ, spot diameter is 0.8 mm, and irradiation density is 36 pulse/mm²⁹⁾. 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 previous irradiated line. The repetition of this process resulted in the irradiation of an area of 10 × 10 mm. The residual stress at center of irradiation area was measured by X-ray diffraction (XRD, the sin² ψ method, collimator diameter: 2mm) using Cr-K α (17 kV, 2.0 mA) as the X-ray source.

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 sin² ψ method are listed with the confidence intervals (1σ) after the $\pm$ symbols. The confidence interval has ± 30 MPa at maximum but is mostly around ± 10 MPa. The spots that were not laser peened have compressive residual stresses around -6 to -70 MPa for σ_x and σ_y , respectively. This stress was probably generated during the cooling of the manufacturing process for the steel plate. As for the laser peened spots, significant compressive residual stresses around -170 to -190 MPa were generated for σ_x , and -300 to -330 MPa for σ_y . Comparing the residual stress components σ_x and σ_y , the former tends to result in greater compressive residual stress. This phenomenon is also seen in other materials after laser peening and needs further investigation. The difference 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 the peening conditions employed for SM490 are applied for the high-strength steel.

4. Surface residual stress in boxing toe

Figure 1 shows the shape and dimensions of the specimen, in which an all-round fillet (one-pass, measured leg length: 7 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 and groove was not prepared. CO₂ arc welding was employed and solid wire for the 780 MPa grade steel was used as the welding material. Table 1 and 2 list the catalogue values for the mechanical properties and

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 compositions

	Chemical composition (%)										
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B
	$\times 10^{-2}$		$\times 10^{-3}$		$\times 10^{-2}$			$\times 10^{-3}$			
HT780-1	19	23	145	9	1	-	-	-	-	-	1
HT780-2	15	36	120	12	1	1	1	10	12	0	1
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

	Residual stress (MPa)					
	Without laser peening		With laser peening		Change by laser peening	
	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
HT780-1	-44 $\pm$ 18	-35 $\pm$ 30	-174 $\pm$ 6	-312 $\pm$ 8	-131	-278
HT780-2	-6 $\pm$ 13	-70 $\pm$ 7	-191 $\pm$ 3	-330 $\pm$ 6	-185	-260

Fig. 1 Specimen for residual stress measurement

chemical compositions of the wire. The welding voltage, the welding current and the welding speed were 25-27 V, 200-210 A and about 180 mm/min, respectively. 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.

First, the residual stresses near the upper and lower boxing toes were measured. Then an area of 40×20 mm around the boxing toes was laser-peened and residual stresses at the same positions

Fig. 2 Measuring points of XRD

were measured. Figure 2 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 laser irradiation is indicated in x in Fig. 1. Figures 3 and 4 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 ○), compressive residual stresses of around 100 MPa were measured at point E, which is close to the edges of the specimen, while the stresses were measured to be almost 0 MPa at other points. After laser peening (indicated by ●), no change in residual stresses 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 residual stresses. In particular, point C, which is closest to the toe where fatigue cracking is initiated, shows the largest change in residual stresses due to laser peening. It is therefore estimated that significant compressive residual stress is also generated near the boxing toe. These are the same results in the case of SM490.

(a) A-B-C-D-E line

(a) A-B-C-D-E line

(b) C-F-G-H line

(b) C-F-G-H line

Fig. 3 Results of surface residual stress measurement (σ_x)

Fig. 4 Results of surface residual stress measurement (σ_y)

5. Distribution of residual stress in thickness direction

The distribution of the Y-direction component (σ_y) of the residual stress at point C of laser-peened specimen in the thickness direction was estimated by repeating residual stress measurements using XRD and electrolytic polishing. Figure 5 shows the results of the measurement. The laser-peened specimen showed a large residual stress of over -500 MPa at a depth of around 0.2 mm. Although the compressive residual stress gradually became smaller with depth beyond 0.4 mm, a compressive residual stress of about -100 MPa remained even at a depth of 0.8 or 1.0 mm. Consequently, it was shown that the toe surface of the butt-welded joint had a large compressive residual stress produced by laser peening up to a depth of about 0.8 mm.

6. Effect of laser peening on fatigue life

Fatigue tests were performed on laser-peened and unpeened specimens for a quantitative investigation to determine whether the fatigue life in the boxing toe of HT780 was prolonged by laser peening.

Fig. 5 Distribution of residual stress in the thickness direction (σ_y)

6.1 Experiment overview

Using a 300 kN uniaxial fatigue testing machine, fatigue tests were performed in constant stress ranges for the unpeened specimens (hereafter, called NP) and the laser-peened specimens (hereafter, called LP). The fatigue test was also performed for flat bar specimens (hereafter, called FB), which have no rib and box welding.

Figure 6 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 are as mentioned in the section of residual stress in box toe. The position and the area of laser peening are shown in Figures 6 and 7. The laser peening conditions are the same as mentioned in the section of residual stress in base metal.

For the stress range to be loaded, there are two LPs each at 300, 350, 400, 450, 500, and 600 MPa, one at 550 MPa, making a total of 13 specimens; three NPs at 200 and 250 MPa, two each at 300, 350, 400, 450, 500, 550, and 600 MPa, making a total of 20 specimens; there are two FBs each at 350, 400, 450, 500, 550, and 600 MPa, making a total of 12 specimens. The stress ratio was 0, and the censored limit was set at 10^7 times.

Fig. 6 Specimen for fatigue test

Fig. 7 Photograph of a box-welded rib specimen and its laser-peened area

6.2 Experiment results

Figure 8 shows the S-N diagram obtained from the experiment. The arrows in the figure indicate that the number of fatigue reached censored limits without fatigue fracture.

Figure 9 shows photographs of the fracture surfaces. The mark ● in the figure represents the crack-initiation point, while the arrows show the direction in which cracking propagate. In the case of all NPs, crack initiation occurred at the boxing toe, where large stress concentration exists. In the case of LPs exceeding 450 MPa, crack initiation occurred at the boxing toe. 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. In the case of all FBs, crack initiation occurred at border of parallel part and fillet part (named “(R)” in Fig. 8) of the base plate.

Three NPs in the 200 MPa stress range and one out of three in the 250 MPa range reached the censor limit; 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.

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 70×10^5 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, which is the fatigue limit of FBs.

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.

Figure 10 shows a comparison between the fatigue lives of NPs and LPs in each stress range. The vertical axis represents how much times the fatigue life of each LP is longer when the average

fatigue life of two NPs in each stress range NP_{AVE} was 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

(a) NP (All stress ranges)

(b) LP ($\Delta\sigma = 350$ and 400 MPa)

(c) LP ($\Delta\sigma = 450 - 600$ MPa)

Fig. 9 Fracture surface

Fig. 8 S-N diagram

Fig. 10 Comparisons between NP and LP

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.

7. Conclusions

This study targets 780 MPa grade high-strength steel (HT780) in order to clarify whether laser peening generates compressive residual stresses on the surface of HT780, and whether such stresses would account for prolonged fatigue life in the welded zones of HT780. The results can be summarized as follows.

- (1) Large compressive residual stresses were generated on the base metal surface of HT780 under the same peening conditions employed for 490 MPa grade steel.
- (2) Laser peening generated significant compressive residual stresses around the boxing toe of HT780, where fatigue cracking is usually initiated.
- (3) The compressive residual stress at the boxing toe is produced up to a depth of about 0.8 mm caused by laser peening.
- (4) In the laser-peened boxing toe specimen of HT780, crack initiation site varied depended on the stress range. For the stress ranges of 350 and 400 MPa, cracks were initiated from the back side of the toe where no stress concentration was observed.
- (5) The fatigue limit of the boxing toe of HT780 was improved by at least 1.5 times as a result of laser peening.
- (6) The smaller the stress range, the greater was the improvement of the fatigue life of boxing toe of HT780 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 large and deep compressive residual stress, which remarkably extended the fatigue life of this part.

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