Welding Letters Vol.41 No.4 (2023) p.1 WL-4 WL DOI: 10.2207/qjjws.41.1WL

WELDING LETTERS

Effect of Laser Peening on Fatigue Properties of Butt-Welded Joints with Angular Distortion

Tomoharu Kato[a, b,*], Yoshihiro Sakino[c], Yuji Sano[d,e,f], Yasuyuki Kurihara[g], Yoshio Mizuta[e] and Satoshi Tamaki[e]

[a] *Graduate School of Systems Engineering, Kindai University, Higashihiroshima 739-0042, Japan*
[b] *Research Fellow of Japan Society for the Promotion of Science, Tokyo 102-0083, Japan*
[c] *Faculty of Engineering, Kindai University, Higashihiroshima 739-0042, Japan*
[d] *Institute for Molecular Science, National Institutes of Natural Sciences, Okazaki 444-8585, Japan*
[e] *SANKEN, Osaka University, Ibaraki 567-0047, Japan*
[f] *LAcubed Co., Ltd., Yokohama 220-0012, Japan*
[g] *Steel Research Laboratory, JFE Steel Corporation, Kawasaki 210-0855, Japan*

Laser peening (LP) is a well-established technique for introducing compressive residual stress (RS) near the surface of metal components to improve their high-cycle fatigue properties. In this study, butt-welded joint specimens of SBHS500 steel with angular distortion were prepared and treated with LP. X-ray diffraction showed that the maximum compressive RS over 400 MPa was introduced near the surface by applying LP with an irradiated pulse energy of 7.5 mJ, a spot size of 0.42 mm, and a pulse density of 800 pulses/mm^2. The effect reached a depth of approximately 0.15 mm from the surface. The specimens were subjected to a uniaxial fatigue test with a stress ratio of 0.1 together with specimens without LP. The results showed that the fatigue life was prolonged by LP. However, in the stress range of 300 MPa, the detrimental effect of angular distortion predominates over the beneficial effect of LP, showing that the fatigue life extension by LP is not evident.

***Key Words*: Laser peening, High-strength steel, Butt-weld, Angular distortion, Fatigue strength**

1. INTRODUCTION

Welding is one of the most common joining processes in steel construction. The welding process causes residual stresses and deformations that result from the restraint of the adjacent base metal as the molten metal shrinks. In the longitudinal direction, strain and buckling result from shrinkage along the weld. While, in the transverse direction, angular distortion results from shrinkage perpendicular to the weld. Eliminating all such welding defects is desirable, but minor defects are acceptable because of economic rationality and technical difficulties. Angular distortion in welded joints increases the strain concentration at the weld toe, so the fatigue strength of welded joints with angular distortion is lower than that of those without angular distortion.

Iida et al. prepared butt-welded joint specimens with initial angular distortion for two types of materials – WES HW50 steel and HW70 steel – and conducted axial-load controlled fatigue tests[1)]. The results showed that the fatigue strength of specimens decreases as initial angular distortion increases. Thus, some studies have investigated the effect of butt-welds' initial angular distortion on fatigue strength, but such studies remain few[1,2,3)].

Laser peening (LP) improves fatigue strength[4)]. LP introduces compressive residual stress (RS) on the surface of metallic components covered with water by irradiating successive high-intensity laser pulses. This is highly effective for preventing fatigue cracks in load-bearing components subjected to cyclic loading. In LP, peening intensity can be instantaneously controlled by adjusting process parameters such as laser pulse energy and irradiation density corresponding to "coverage" of shot peening. Furthermore, LP can be applied to objects with complicated surface structure by real-time control of the focal position of irradiated laser pulses. Furthermore, microchip laser technology can drastically reduce the size and weight of laser oscillators[5)]. If a microchip laser could be used as the energy source for LP, the size of LP devices could be reduced, which would enable application of LP not only to production but also to on-site maintenance of existing infrastructure such as bridges in service.

In this study, we applied LP to welded joint samples of SBHS500 steel with a pulse energy of about 8 mJ attainable using the portable LP device to compensate for the reduction of fatigue strength by angular distortion. First, we performed fatigue tests using butt-welded specimens with angular distortion to understand the detrimental effect on the fatigue strength. Next, we laser-peened SBHS500 base metal to select the conditions for introducing favorable compressive RSs. Then, we applied LP to butt-welded specimens with angular distortion and conducted uniaxial fatigue tests with a stress ratio of 0.1.

2. MATERIAL AND METHODS

2.1 Chemical composition and mechanical properties

The material used in this study was a 570-MPa-grade higher yield strength steel plates for bridges (SBHS500). The chemical composition and mechanical properties of

receivedber: 2023.2.24 ; accepted: 2023.5.9
*Corresponding author
E-mail address: 2244830001h@hiro.kindai.ac.jp

SBHS500 and welding wire are listed in Table 1.

2.2 Preparation of fatigue samples with angular distortion

Two 6-mm-thick SBHS500 plates were beveled and butt-welded by CO_2 gas-shielded arc welding using a solid wire of 570-MPa-grade steel. The V-groove was filled by two layers on the front side and one layer on the back. The welding conditions were a current of 180 A, a voltage of 22 V and a speed of 2 mm/s. The butt-welded joint was sawn into 30-mm-wide pieces and finished by machining to the prescribed shape and dimensions shown in Figure 1. Both side surfaces were finished by polishing, while the mill-scale caused by hot-rolling remained on the front and back surfaces.

The specimens were plastically deformed at the weld by a three-point flexural test so that the groove side was convex with an angular distortion of e = 2, 6, or 10 mm for a span of 110 mm, as shown in Figure 1. The specimens without angular distortion (e = 0 mm) and with angular distortion (e = 2, 6, 10 mm) are referred to as 0/110, 2/110, 6/110, and 10/110 specimens, respectively.

The center area of 20 mm × 9 mm including the weld metal and heat-affected zone (HAZ) was laser-peened on both front and back surfaces.

2.3 Portable LP device

Figure 2 shows the configuration of the portable LP device using a thumb-sized Nd:YAG microchip laser mounted on a 6-axis collaborative robot arm[6]. The system comprises the robot arm with the microchip laser, a power supply and water circulation system, and a control PC. The system can be stored in two packages, and each package can be transported as airline baggage.

The power supply is equipped with a semiconductor laser that pumps via a fiber optic cable the microchip laser mounted on the robot arm. The water circulation system ejects water coaxially with the laser pulse from a nozzle at the tip of the laser and collects the used water for reuse. The collaborative robot eliminates the need for the installation of safety measures such as fences. The robot arm weighs 4 kg and has a payload of 0.5 kg. All devices operate on AC 100 to 220 V and the maximum power consumption is less than 400 W.

2.4 RS measurement using X-ray diffraction

Surface RSs were measured using X-ray diffraction (XRD) with a cosine α method[7], which deduces surface RS state by evaluating the distortion of the Debye–Scherrer ring. In the present study, Cr-kα characteristic X-rays irradiated the sample via a collimator with a diameter of 1 mm, and the diffracted X-rays from α-Fe211 planes were collected using an area detector. The XRD device was rocked over 10° to obtain a smooth diffraction pattern and to reduce the standard deviation of the resulting regression.

The RS distribution in the direction of sample thickness was estimated by alternately repeating XRD and electrolytic polishing. In this process, RS is measured at the bottom of a locally polished sample with a diameter of approximately 6 mm, and the measured RS is regarded as the approximate values at the depth of the unpolished sample. This method does not provide the exact RS distribution because the RS is redistributed by polishing. However, when the polishing is shallow, the error introduced is small, as shown by comparison with RSs measured non-destructively in a synchrotron radiation facility[8].

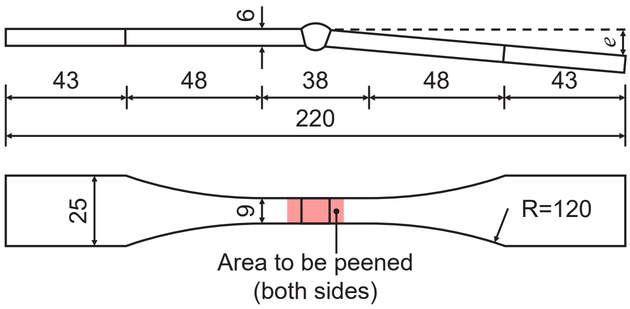

Figure 1. Butt-welded specimen of SBHS500 with angular distortion

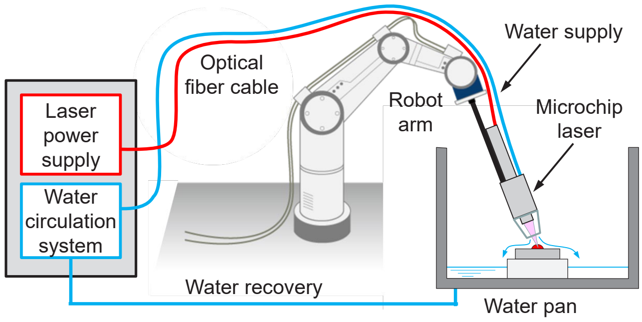

Figure 2. Configuration of portable LP device

Table 2. LP conditions with microchip laser for SBHS500

Laser wavelength (μm)	1.06
Irradiated pulse energy (mJ)	7.5
Pulse duration (ns)	1.3
Spot diameter (mm)	0.42
Peak power density (GW/cm^2)	4.2
Pulse repetition rate (Hz)	100
Pulse density (pulse/mm^2)	800

Table 1. Chemical composition and mechanical properties of SBHS500 and welding wire

Material	Chemical composition (10^{-2} wt.%)						Mechanical properties			
	C	Si	Mn	P	S	Ceq	0.2 proof stress (MPa)	Tensile strength (MPa)	Elongation (%)	Yield ratio (%)
SBHS500	9	23	144	0.5	0.1	41	592	625	30	95
Welding wire*	7	52	144	1	0.6	-	590	650	25	-

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

3. EXPERIMENTAL

3.1 LP conditions

Table 2 summarizes the LP conditions for the SBHS500 base metal and welded joint specimens. These conditions are based on those reported by Sano et al.[5)], under which sufficiently large compressive RSs were produced on a 780-MPa-grade structural steel. LP was performed without any surface coating (sacrificial overlay) on the specimens using the portable LP device. During the LP treatment, the sample was immersed in water to prevent water splash.

After confirming that compressive RSs were introduced on the surface of the base metal specimen, LP was applied to both front and back sides of the central part including the weld metal and HAZ on the 0/110 and 6/110 specimens. The LP conditions were 7.5-mJ pulse energy, 0.42-mm spot diameter, and 800-pulse/mm^2 irradiation density as listed in Table 2, which were optimized with respect to the RS of the SBHS500 base metal.

3.2 Fatigue testing

Strain gages were glued on the front and back surfaces of each specimen. Each specimen was then mounted on a uniaxial fatigue testing machine so that the angular distortion was corrected to be straight, and the strain at the weld toe was measured to confirm the initial strain before fatigue testing. Then, the 0/110, 2/110, 6/110, and 10/110 specimens described in Section 2.2 were subjected to fatigue tests with a stress range ($\Delta\sigma$) of 250 MPa and a stress ratio (R) of 0.1. Some specimens with angular distortions of 0/110 and 6/110 were subjected to LP followed by fatigue tests with stress ranges ($\Delta\sigma$) of 200, 250, and 300 MPa.

4. RESULTS AND DISCUSSION

4.1 Effect on RS of SBHS500 base metal

Specimens of the SBHS500 base metal were laser-peened using the portable LP device. The RS depth profiles were obtained by alternately applying XRD and electrolytic polishing as described in Section 2.4. The same procedure was also applied to the unpeened material, and the results were compared to evaluate the effect of LP on RS. Figure 3 shows the RS depth profiles of the SBHS500 base metal in the direction perpendicular to the laser scanning direction of LP treatment. The standard deviation of the RS measurements was about ± 10 MPa. While RSs of the unpeened material are almost 0 MPa, the laser-peened specimen shows large compressive RSs of over 400 MPa near the surface and the depth reached approximately 0.15 mm from the surface.

4.2 Effect of angular distortion on fatigue strength of butt-welded specimens

The strain at the weld toe of the specimens when mounted to the fatigue testing machine is shown in Figure 4. The 0/110 and 2/110 specimens showed almost no strain, which suggests that the correction of 2 mm angular distortion for the 110-mm span by mounting to the fatigue testing machine has negligible effect on the strain at the weld toe. The strains of the 6/110 and 10/110 specimens changed significantly by mounting on the fatigue testing machine; the correction of the angular distortion of 6 mm or more affected the strain at the weld toe.

Figure 5 shows the fatigue test results for the 0/110, 2/110, 6/110, and 10/110 specimens. All specimens showed a fatigue crack starting from the weld toe on the concave side. The 0/110 and 2/110 specimens failed between approximately 150,000 and 370,000 cycles. Because the difference in the fatigue lives was small, the angular distortion of less than 2 mm for the 110 mm span had almost no effect on the fatigue life. The specimens with larger angular distortions, the 6/110 and 10/110 specimens, failed after approximately 90,000 cycles; this was much lower than the failure lives of the 0/110 and 2/110 specimens. The fatigue life decreased significantly when angular distortion exceeded 6 mm or more in the present study. This can be attributed to the effect of secondary bending due to angular distortion.

4.3 Effect of LP on fatigue strength of butt-welded specimens with angular distortion

There was a significant difference between the fatigue lives of 0/110 and 6/110 specimens. In this section, the effects of LP on the fatigue life of the specimens with and without angular distortion are compared.

Figure 6 shows the S-N curves of the fatigue test results for the SBHS500 welded joint samples. The results for laser-peened specimens are shown in white and the results for the unpeened reference are shown in black; the results for specimens without angular distortion (0/110) are shown as circles and the results for the 6/110 specimens are shown as squares. Fatigue cracks were initiated from the concave side of the angular distortion in all specimens.

At the stress range of 200 MPa, the fatigue life was prolonged by LP; specimens after LP reached the censoring limit of 10^7 cycles with and without angular distortion. In the stress range of 250 MPa, the fatigue life of the 0/110 specimen with LP was prolonged compared with that without LP. The fatigue life of the 6/110 specimen with LP was also prolonged compared with that without LP, but those fatigue lives were less than that of the 0/110 specimen without LP. In the stress range of 300 MPa, the fatigue life of the 0/110 specimen with LP was prolonged compared with the specimen without LP, but the fatigue lives of the 6/110 specimens with LP were nearly the same as those of the specimens without LP.

In the low stress range, the LP effect was confirmed to prolong the fatigue life of the butt-welded specimens with angular distortion. However, in the higher stress range, the effect of LP was not so evident because the effect of angular distortion was greater than the effect of LP.

5. CONCLUSIONS

Butt-welded joint specimens of SBHS500 steel with angular distortions were prepared, treated with LP, and subjected to uniaxial fatigue tests. The results obtained through this study are itemizes as follows:

(1) There was a negligible effect on fatigue strength when angular distortion was less than 2 mm for the 110-mm span, but a significant effect was found when angular distortion exceeded 6 mm.
(2) LP of SBHS500 steel was performed; compressive RS was generated with a magnitude exceeding 400 MPa and a depth of compression of approximately 0.15 mm.
(3) The butt-welded specimens were subjected to fatigue tests with a stress range of 200, 250, and 300 MPa at a stress ratio of 0.1. The results showed that the fatigue life was prolonged by LP. However, in the stress range of 300 MPa, the effect of angular distortion was greater than the effect of LP, and consequently the fatigue life was not extended by LP.

Acknowledgments

This work was partially supported by the Supporting Industry Program of the Small and Medium Enterprise Agency [grant number 202041907014]; the JST-MIRAI Program [grant number JPMJMI17A1]; JSPS KAKENHI [grant number 19H02228]; the Amada Foundation [grant number AF-2020239-C2]. This research was a part of activities carried out by an ad hoc research group supported by Japan Welding Society.

References

1) K. Iida and N. Iino: Effect of Angular Distortion on Fatigue Strength of Transverse Butt-Welds in High Strength Steels, Transactions of the Japan Welding Society, 8-2 (1977), 83-90.
2) M. J. Ottersböck, M. Leitner and M. Stoschka: Impact of Angular Distortion on the Fatigue Performance of High-Strength Steel T-Joints in as-Welded and High Frequency Mechanical Impact-Treated Condition, Metals, 8-5 (2018), 302.
3) Y. Akita, T. Yoda and K. Sakai: Low Cycle Fatigue Strength of Welded Joint with Angular Distortion in 80 kg/mm^2 Class High Tensile Steel, Journal of the Society of Naval Architects of Japan, 1968-123 (1968), 316-322.
4) Y. Sano: Quarter Century Development of Laser Peening without Coating, Metals, 10-1 (2020), 152.
5) L. Zheng, A. Kausas and T. Taira, >30 MW peak power from distributed face cooling tiny integrated laser, Optics Express 27-21 (2019), 30217-30224.
6) Y. Sano, T. Kato, Y. Mizuta, S. Tamaki, K. Yokofujita, T. Taira, T. Hosokai and Y. Sakino: Development of a portable laser peening device and its effect on the fatigue properties of HT780 butt-welded joints, Forces in Mechanics, 7 (2022), 100080.
7) K. Tanaka: X-ray measurement of triaxial residual stress on machined surfaces by the cosα method using a two-dimensional detector, Journal of Applied Crystallography, 51 (2018), 1329-1338.
8) Y. Akiniwa and H. Kimura: Determination of Residual Stress Distribution in Severe Surface Deformed Steel by Shot Peening, Materials Science Forum, 571-572 (2008), 15-20.

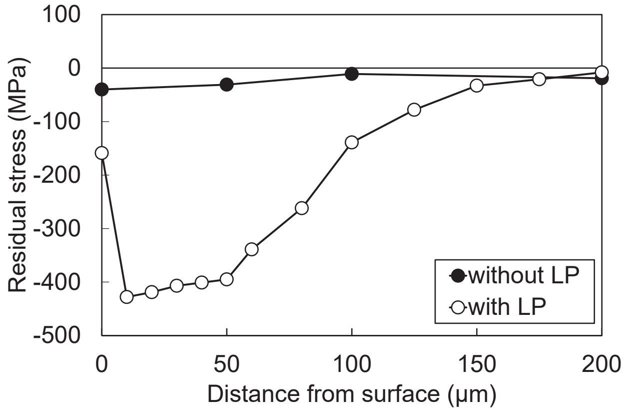

Figure 3. Residual stress depth profiles of SBHS500

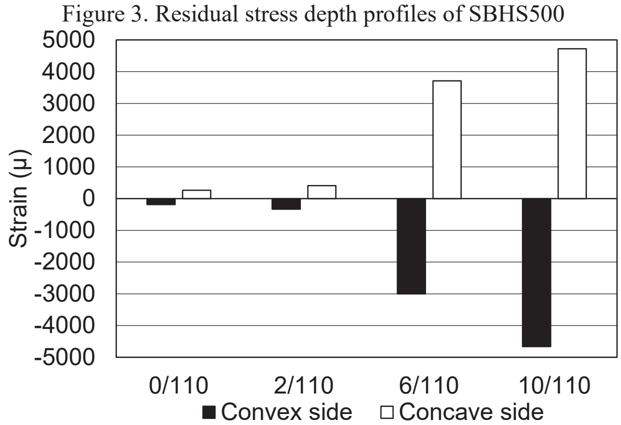

Figure 4. Initial strain at weld toes after mounting specimens with angular distortion on fatigue testing machine

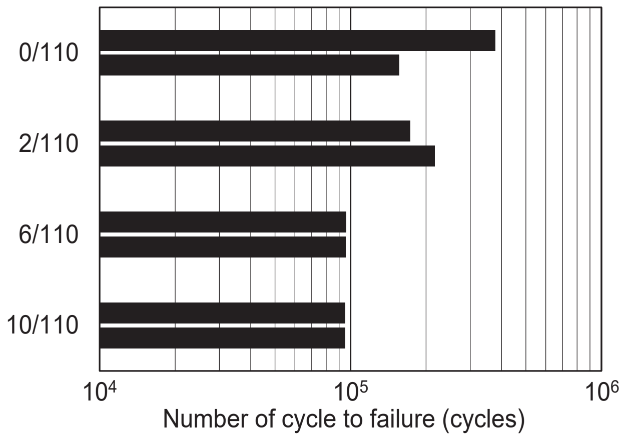

Figure 5. Fatigue test results for specimens with angular distortions

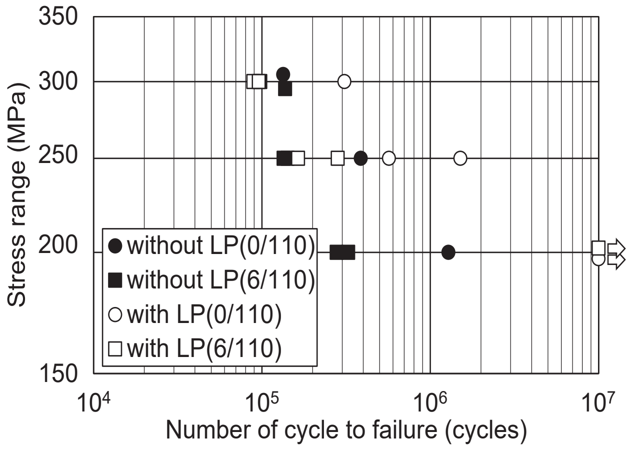

Figure 6. Effects of angular distortion and LP on fatigue life