Application of Friction Stir Processing to Weld Toe for Fatigue Strength Improvement of High-Strength Low-Alloy Steel Joint

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Fatigue strength of fusion-welded joints is lower than that of the base metal, due to stress concentration, tensile residual stress, and microstructural degradation at the weld toe. To improve these issues, friction stir processing (FSP) was applied to the weld toe of high-strength low-alloy steel joints using a newly developed tool with a conical shoulder. With use of FSP, the weld toe geometry and microstructure were successfully modified without defect formation in the stir zone (SZ). Hardness was increased due to significant grain refinement and compressive residual stress was produced on the weld surface. Fatigue strength and life of the FSP-modified welded specimens was improved, though not largely, since a new stress concentration region with reduced plate thickness and serrated surface was produced by the shoulder edge of the FSP tool, just beside the base metal. Fatigue cracks initiated there and propagated in the SZ, thermo-mechanically affected zone, and base metal for the FSP-modified welded specimens. The fatigue strength could be further increased by prevention of the stress concentration at the SZ edge.

Key Words: Friction stir processing (FSP), High-strength low-alloy (HSLA) steel, Fatigue strength, Weld toe, Grain refinement

1. INTRODUCTION

Friction stir processing (FSP), which is based on the principle of friction stir welding (FSW), is an effective surface modification technique using a rotational tool to refine and homogenize microstructure of various metallic materials¹⁾. Mechanical properties of a stir zone (SZ) produced locally by FSP such as strength, ductility, and fracture toughness can become superior to those of the base metal²⁻⁷). The advantages of FSP are adapted for fusion welds as post-weld treatment, since fatigue strength of the welded joints is lower than that of the base metal because of generated stress concentration and tensile residual stress, and microstructural degradation at the weld toe. Costa et al.⁸⁻¹¹ reported that grain refinement and stress concentration reduction due to FSP at the weld toe increased fatigue strength of several aluminum alloy joints fabricated by metal inert gas welding. FSP can be used as a new technique to increase fatigue strength of the fusion-welded joints, and provides advantages different from grinding¹²⁻¹⁴) and remelting¹⁵⁻¹⁷) for the weld geometry modification or peening¹⁸⁻²⁰) and post-weld heat treatment²¹⁾ for decreasing tensile residual stress. However, use of the FSP technique has been limited to a few light metal alloy welds so far, since the process window of FSP for other hard materials is small. On the other hand, FSP might possibly be effective for modifying soft or brittle microstructure related to phase transformation in the heat-affected zone (HAZ) in the steel joints.

We have reported that application of FSP on the topmost layer of tungsten inert gas (TIG) welds on SS400

mild steel plates could increase three-point bending fatigue strength of the welds²²⁾. Significant grain refinement in the SZ of the topmost layer of the TIG welds was observed, and it could be a reason for the increased fatigue strength (prevention of crack initiation). However, aspects of the FSP specification such as a tool geometry and execution of works do not apply directly to the weld toe of steel joints. In this study, using a newly developed FSP tool with a conical shoulder, surface modification of the weld toe in the steel joints was performed using tilted FSP, and the effects on the fatigue strength were investigated.

2. EXPERIMENTAL PROCEDURE

High-strength low-alloy (HSLA) steel with a chemical composition of Fe–0.14C-0.23Si-1.08Mn-0.014P-0.006S-0.01Cu-0.01Ni-0.02Cr-0.002V-0.028A1 (mass%) was used for the base metal in this study. Multi-pass CO₂ arc welding on V-groove with a root gap of 5 mm was conducted on 10-mm-thick HSLA steel plates using MX-Z200 filler metal. The flank angle of the last deposited excess weld metal was 125°.

FSP was performed along the weld toe of the last deposited excess weld metal at a travel speed of 100 mm/min with a clockwise rotation at a rotational speed of 200 rpm with about 24 kN in applied load control in Ar atmosphere. The butt-welded steel plates were put on a specially prepared anvil with a tilt angle of 16° as shown in Figure 1(a). A WC-6%Co tool having a 12-mm-diameter conical shoulder with an apex angle of 140° and a 1.6-mm-long by 4-mm-diameter probe indicated as Fig. 1(b) was roughly fitted in the flank angle of the excess weld metal. The retreating side (RS) and advancing side (AS) during FSP were located on the base metal and excess weld metal sides, respectively.

received: 2018.2.27; accepted: 2018.5.23

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Fig. 1 Schematic illustrations of (a) FSP application to the weld toe and (b) FSP tool geometry.

Microstructure observation of the specimens with and without FSP was conducted using optical microscopy (OM) and scanning electron microscopy (SEM). The polished cross-sectional plane was etched with 2% nital solution. On the plane beneath the surface, Vickers hardness tests were performed at room temperature (RT) with an applied load of 9.8 N and loading time of 30 s.

Residual stresses were also measured on the surface around the weld toe of the specimens with and without FSP in the transverse direction to the weld bead using a two-dimensional X-ray diffraction (XRD) detector employing Cr- $K\alpha$ radiation with a 1-mm-diameter collimator. They were estimated based on *d*-spacing, which is the distance between atomic layers in a crystal, with the $\{2\ 1\ 1\}_{\alpha-Fe}$ planes using the cos α technique.

Four-point bending fatigue tests were performed at RT with a sinusoidal waveform of 20 Hz as a function of maximum applied stress with a stress ratio of 0.1. Outer and inner spans of 10-mm-diameter pins were 60 and 20 mm, respectively. The weld toe was located at the center of the inner pin span, where both base metal and excess weld metal parts were included.

3. RESULTS AND DISCUSSION

Figure 2 shows cross-sectional OM images of microstructure in the as-welded specimens. The base metal (Fig. 2(b)) and coarse-grained HAZ (CGHAZ) at the weld toe (Fig. 2(c)) exhibited ferrite-pearlite structure and upper bainite structure, respectively. The weld metal mainly consisted of acicular ferrite structure, with the finest grains in the as-welded joint (Fig. 2(d)). Figure 3 shows cross-sectional OM and SEM images of microstructure in the FSP-modified welded specimen. FSP could be performed at the weld toe without obvious defects. Weld and base metals were mixed at in the weld area and formed about a 3-mm-thick SZ consisting of ultrafine grains. The base metal region was extended to the weld metal region due to plastic flow on the AS of the SZ, and vice versa, as shown in Fig. 3(b). The pearlite fractured into small pieces was observed in the prior base metal region (Fig. 3(c)). The morphology was similar to that reported in the FSWed low carbon steel without phase transformation²³⁾. This suggests



Fig. 2 (a) A cross-sectional OM image of the as-welded steel plate, and (b)-(d) enlarged images in the positions depicted by b-d in (a).



Fig. 3 (a) A cross-sectional OM image of the FSP-modified welded specimen, and enlarged (b), (e), (f) OM and (c), (d) SEM images in the positions depicted by b-e in (a) and f in (e).

the peak temperature during FSP can be below the A₁ point, although it was not measured in this study. Their ferrite grain sizes of about 2 µm were larger than those of the prior weld metal region (Fig. 3(d)). This effect can be explained by difference of grain size in the initial weld and base metals^{24, 25)}. FSP modified the weld toe geometry as well as the microstructure. An obvious increase in the weld toe radius was observed, depending on the tool geometry. However, the plate thickness was reduced by about 0.5 mm on the RS of the SZ (Fig. 3(e)), since the tilted tool caused gouging of the base metal during FSP. The thermo-mechanically affected zone (TMAZ) beneath the serrated surface showed microstructure consisting of elongated grains (Figs. 3(f)).

Figure 4 shows Vickers hardness distributions beneath the surface of the as-welded and FSP-modified welded specimens. The average hardness of the base metal was about 151 HV. The weld metal consisting of fine grains exhibited the highest hardness in the as-welded specimens. The CGHAZ hardness at the weld toe was similar to that of the weld metal. Grain refinement provided by FSP increased the hardness in the SZ over an area of about 10 mm in width to a range between 210 and 260 HV, an increase of about 40 HV. The variation was attributed to difference of the grain size, depending on the initial



Fig. 4 Vickers hardness distributions beneath the surface of the as-welded and FSP-modified welded specimens.

microstructure. The hardness of the prior weld metal region with finer grains was higher than that of the prior base metal region in the SZ. The higher hardness was exhibited at the base metal right next to the SZ, which corresponds to the TMAZ, compared to that of the prior base metal, because of dominant plastic deformation.

The transverse residual stress distributions measured by XRD on the surface of the as-welded and FSP-modified welded specimens are shown in Figure 5. The specimen shape was the same as that prepared for fatigue tests. There was little tensile residual stress, about 5 MPa, left at the weld toe of the as-welded specimen (rightmost triangle), while FSP provided compressive residual stress in the whole SZ. The compressive residual stress around the weld toe was about 100 MPa. The maximum value, estimated to be about 300 MPa, was observed at the base metal right beside the RS of the SZ, where the tilted tool caused gouging of the base metal. The residual stress on the SZ surface produced by FSW for the several flat HLSA steel plates has been reported to become tensile due to thermal contraction during the cooling time²⁶⁻²⁸⁾. The FSP heat input and SZ volume in this study were much less than those of the conventional FSW in terms of the process parameters. Thus, compressive residual stress in the SZ could be attributable to plastic deformation by FSP rather than the thermal contraction.

Fatigue performance of the FSP-modified welded



Fig. 6 S-N diagram for the as-welded and FSP-modified welded specimens.



Fig. 5 Residual stress distributions on the surface of the as-welded and FSP-modified welded specimens.

specimens was investigated, and the relationship between the applied stress amplitude and number of cycles to failure (S-N diagram) is shown in Figure 6, together with those of the as-welded specimens. Fatigue life of the FSP-modified welded specimens was longer than that of the as-welded specimens at every applied stress amplitude. The stress amplitudes without failure at 2×10^6 cycles (arrow) were estimated to be about 125 MPa and 100 MPa as fatigue limit in the FSP-modified welded and as-welded specimens, respectively. The increase in fatigue limit due to FSP was about 25 MPa, while that at $4-5 \times 10^4$ cycles (250 MPa in stress amplitude) was little. This trend is often seen in several peening methods¹⁸⁻²⁰⁾ because residual stress relaxation due to plastic deformation is large in the high stress amplitude during fatigue. Fatigue cracks initiated at the weld toe and propagated in the CGHAZ in the as-welded specimen, as shown in Figures 7(a) and 7(c). In contrast, cracks initiated at the SZ, corresponding to the position of the gouging caused by the FSP tool, just beside the base metal in the FSP-modified welded specimen, and propagated in the SZ, TMAZ, and base metal (Figs. 7(b) and 7(d)). Consequently, FSP could prevent the fatigue failure originally occurring at the weld toe, and moved its location slightly toward the SZ edge with the reduced thickness and serrated surface, leading to the increase in fatigue strength. However, a serious stress concentration at



Fig. 7 Cross-sectional OM images of microstructure in the (a), (c) as-welded and (b), (d) FSP-modified welded specimens after fatigue tests at stress amplitude of 150 MPa.

the surface cannot achieve an enormous increase. The increase at low stress levels could be explained by the compressive residual stress and grain refinement produced by FSP. If the stress concentration at the SZ edge were prevented, the fatigue strength could be further increased.

4. CONCLUSIONS

FSP was applied to the weld toe of HSLA steel joints using a newly developed tool. The weld toe geometry and microstructure could be successfully modified, and compressive residual stress was produced. Fatigue strength and life of the FSP-modified welded specimens was improved. However, the improvements were not enormous. The important findings are as follows:

- 1. FSP increased hardness due to significant grain refinement without defect formation in the SZ. Compressive residual stress was produced beneath the FSP-modified weld surface.
- 2. Although the weld toe geometry was improved by FSP, a new stress concentration region was produced on the RS of the SZ, corresponding to the position of the gouging caused by the FSP tool, just beside the base metal.
- 3. Fatigue cracks initiated at the SZ and propagated in the SZ, TMAZ, and base metal in the FSP-modified welded specimens. The stress amplitude was increased by 25 MPa at 2×10^6 cycles as fatigue limit in comparison to as-welded specimens broken at the weld toe.

For further increase in fatigue strength, the stress concentration at the SZ edge should be prevented.

Acknowledgements

One of the authors, Mr. Yamamoto, gratefully acknowledges the financial support from "Program for Leading Graduate Schools: Interactive Materials Science Cadet Program" in Osaka University. The authors would like to thank Mr. Yoshihisa Mishima (X-ray Residual Stress Measurement Center) for the residual stress measurement.

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