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Tensile Residual Stress Mitigation Using Low Temperature Phase Transformation Filler Wire in Welded Armor Plates[1]

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Abstract. Hydrogen induced cracking (HIC) has been a persistent issue in welding of high-strength steels. Mitigating residual stresses is one of the most efficient ways to control HIC. The current study develops a proactive in-process weld residual stress mitigation technique, which manipulates the thermal expansion and contraction sequence in the weldments during welding process. When the steel weld is cooled after welding, martensitic transformation will occur at a temperature below 400 °C. Volume expansion in the weld due to the martensitic transformation will reduce tensile stresses in the weld and heat affected zone and in some cases produce compressive residual stresses in the weld. Based on this concept, a customized filler wire which undergoes a martensitic phase transformation during cooling was developed. The new filler wire shows significant improvement in terms of reducing the tendency of HIC in high strength steels. Bulk residual stress mapping using neutron diffraction revealed reduced tensile and compressive residual stresses in the welds made by the new filler wire.

Introduction

Hydrogen induced cracking (HIC), also called cold cracking or delayed cracking has been a persistent issue in welding of high-strength steels. The main feature of this type of crack is that it occurs in the welds of high-strength martensitic steels, and generally occurs a short time after welding, usually within 48 hours. Fabricating HIC-free structures of advanced high-strength steels (AHSS), particularly the ultra-high-strength grade such as fully hardened martensitic steels used in armored vehicles, can be difficult in field. The existence of HIC poses serious threat to the structural integrity and safe operation of the armor plates.

Four factors contribute to the HIC: susceptible microstructure (usually martensitic microstructure), residual stress, hydrogen content and near ambient temperature. Mitigating residual stress is one of the most efficient ways to control HIC. Weld residual stress is a result of non-

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uniform expansion and contraction in a welded structure. The non-uniform deformations can have a detrimental effect on the integrity of welded structure. Tensile residual stress is very common and may exceed the yield strength of the material in the weld [1,2]. Many studies have shown that tensile residual stress contributes to the high susceptibility of pre-mature fatigue failure [3,4] and hydrogen induced cracking (HIC) in steel welds [5-8]. Post weld heat treatment (PWHT) are the most common way to mitigate tensile residual stress [9]. These techniques include grinding, air hammer peening, shot peening, needle peening and TIG re-melting. Weld toe stress concentration can be reduced by grinding and TIG dressing, however, the tensile residual stress still cannot be entirely eliminated. Furthermore these process have little if any effect on the internal tensile residual stress. On the other hand, the peening processes can both improve weld profile and mitigate tensile residual stress. However, peening requires an extra post weld processing which increases the overall cost of the welded structure. In addition, all of these methods are restrained by the geometry of the weld structure.

In-process residual stress control, which manipulates the thermal expansion and contraction sequence in the weldments during welding process, has recently been developed to mitigate residual stress in steel welds. When the steel weld is cooled after welding, the martensitic transformation will occur at a temperature below 400 °C. Volume expansion in the weld due to transformation will reduce tensile residual stress and in some cases even produce compressive residual stress in the weld. The first LTT filler wire with 10 wt.% Cr and 10 wt.% Ni was developed by Ohta et. al in 2000 [10]. The LTT welds have shown a significant improvement of fatigue lives compared to that of conventional joints [11-13]. However, research on HIC mitigation using LTT filler wire is very limited. Current study applied LTT filler wire principles to mitigate HIC in high-strength armor steels. A special filler wire was designed with martensitic transformation to eliminate HIC in the weld of a high-strength armor steel. Y-groove tests (aka Tekken test) was applied to evaluate the HIC tendency of designed welding filler wire. Neutron diffraction was applied to study residual stress distribution.

Experimental work

Materials and Welding. The chemical composition of high-strength steel base plate MIL-DTL-12560 is shown in Table 1. After initial thermomechanical processing, the steels were normalized at a temperature of 904°C for 21 minutes followed by water quenching. Then the plates were tempered in a furnace at a temperature of 482°C for 39 minutes, followed by cooling in air to room temperature.

Y-groove tests for HIC cracking were performed in accordance with international standard ISO 17642-2. Testing plates are 12.7 mm in thickness. Gas metal arc welding (GMAW) with 95% argon and 5% carbon dioxide cover gas was performed on the plates with one single pass. Welding current, voltage and speed were 230 A, 25.7 V and 3.4 mm/s respectively. LTT experimental filler wires HV1766 with 1.2 mm in diameter were developed and evaluated in current study (see composition range in Table 1). For comparison, commercial ER100 filler wire with similar ultimate tensile strength, SuperArc LA-100 from Lincoln Electric was also used. The wire feed rate was 140 mm/s. Since the formation of cracks in LA-100 Y-groove sample will release tensile residual stress in the plate, the residual stress measured in Y-groove plate with a crack would not accurately represent the residual stress state of the weld made by LA-100 filler wire. As a result, for residual stress analysis, pre-heating at a temperature of 150°C was performed for the plate welded by LA-100 filler wire.

Residual Stress Analysis. The neutron diffraction measurements for the residual stress analysis on Y-groove samples were carried out at the Neutron Residual Stress Mapping Facility (NRSF2) beam line [14] of the High Flux Isotope Reactor, Oak Ridge National Laboratory. The diffraction of neutrons with a wavelength of $\lambda \approx 1.72$ Å on the {211} lattice planes of ferrite/martensite was analyzed. These planes were chosen as the {211} reflection best represents the macro-mechanical behavior of steels [1]. In order to compute the multiaxial residual stress state, the strain of each point

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was determined in transverse, normal and longitudinal direction, with the assumption that the principal stresses lie along these directions. The gauge volume was 2×2×10 mm^3 for transverse and normal directions with exposure time of 200 seconds and 2×2×2 mm^3 for longitudinal direction with exposure time of 600 seconds, taking advantage of sample symmetry. Area of 27×5 mm^2 was mapped for each sample with a grid spacing of 1 mm.

Table 1. Base metal and weld metal composition (in wt.%) and mechanical properties

	C	Mn	Cu	Ni	Cr	Mo	Si	V	Yield Strength [MPa]	Ultimate Tensile Strength [MPa]
MIL-DTL-12560	0.23	1.2	0.17	0.12	0.12	0.45	0.25	0.003	920-980	1000-1040
SuperArc LA-100	0.1	1.8	0.35	0.8	0.2	0.15	0.35	<0.01	730-750	780-790
HV1766	0.05-0.3	0.1-2	0.05-0.5	6-16	6-16	0.1-1	0.1-1	0-1	950-1020	1040-1090

Results

Y-groove Testing Results. The Y-groove test is used to determine HIC sensitivity of welding filler wires. MIL-DTL-12560 Y-grooved plates were both welded by conventional ER100 (LA-100) filler wire and LTT filler wire. The metallographic images of corresponding weld cross section are shown in Fig. 1. A crack throughout the weld in conventional ER100 filler wire indicates ER100 is very susceptible to HIC for MIL-DTL-12560. On the other hand, no crack is seen using HV1766 filler wire. Though the LTT filler wire in the current study shows improved HIC resistance, whether the improved resistance is due to the mitigation of tensile residual stress in the weld is still unclear. As a result, it is important to understand residual stress distribution in the Y-groove welds.

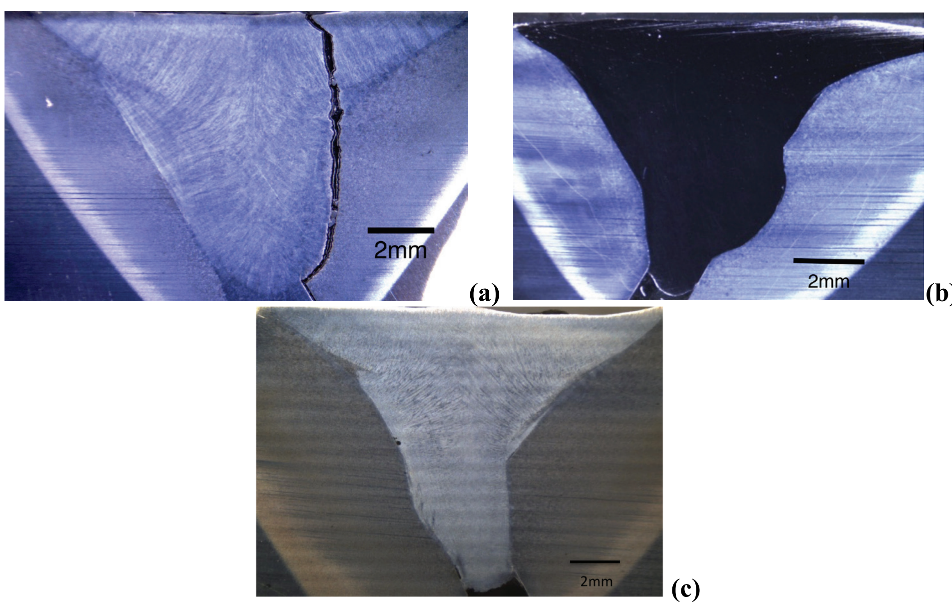

Figure 1. Y-groove test result of (a) SuperArc LA-100 filler wire (b) LTT wire showing cracks in ER100 weld but not in LTPT weld.(c) SuperArc LA-100 filler wire with 150°C preheat

Residual Stress Distribution. Since the weld metal and base metal have very different compositions, a significant spatial variation in stress free lattice spacing, d_0, is expected in the weld, largely due to the change of weld metal dilution from location to location. As a result, accurate determination of d_0 is very challenging. Zhang et al. [15] found the normal stress in 15.2 mm plate with a dissimilar weld is negligible except near fusion boundaries As a result, plane stress can be used as an assumption for the welded plate with thickness of 15 mm or thinner without accurate determination of d_0.

The present analysis procedure is based on the plane stress assumption that the normal stress component σ_Z is equal to zero. This makes it possible to determine the two in-plane stress components σx and σy and stress free lattice spacing using the equations described in [15]. With the plane stress assumption, the residual stress distribution in transverse direction and longitudinal direction within the weld can be calculated. The residual stress map of the area indicated in Fig. 1 (a) is shown in Fig. 2. In addition, the distribution of d0 and full-width at half maximum (FWHM) is also shown in Fig. 2. Due to grain size differences between the weld metal (WM), heat-affected zone (HAZ) and base metal (BM), the FWHM can be used to distinguish these three regions. In Fig. 2 (d), FWHM clearly shows the shape of the weld and these three distinct regions: WM, HAZ and BM. Fig. 2 (a) shows transverse residual stress up to 1000 MPa. Since HIC was observed mainly in the HAZ at a location about 0.2 mm from the fusion boundary (Fig. 1), the transverse residual stress in this location is very important. According to Fig. 2 (a), the transverse residual stress in the HAZ around the fusion boundary is very uniform with a value of 700 MPa in tension.

Maximum longitudinal residual stress in LA-100 is about 1400 MPa in tension, which is much greater than the tensile strength of MIL-DTL-12560 (~1000 MPa). After the welding process, newly formed martensite with high yield strength is expected in the HAZ of MIL-DTL-12560. As a result, the high residual stress of 1400 MPa in HAZ is possible. The WM shows tensile longitudinal residual stresses which range from 200 to 600 MPa. Fig. 2 (c) shows fairly uniform distribution of d_0 in the WM and the BM, which indicates the plane stress assumption is reasonable for the current study in both regions. In the HAZ near the fusion boundaries, two regions show relatively low d0 values. Normal stress may not be zero in these two regions.

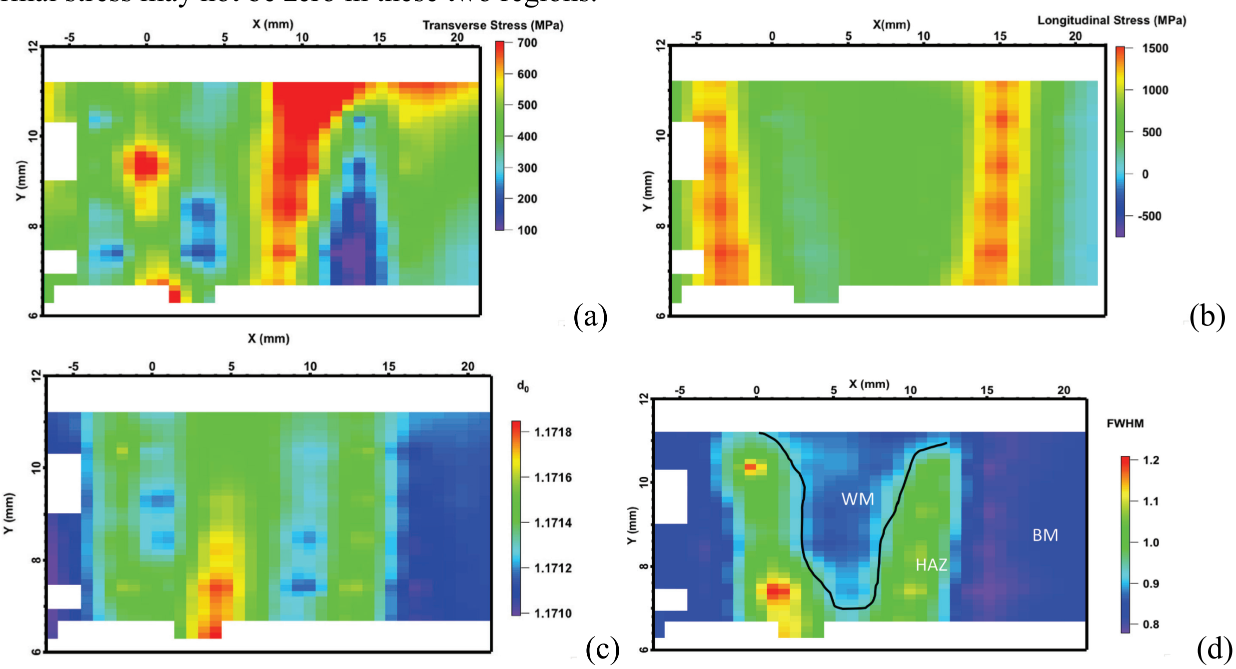

Figure 2. Residual stress distribution of Y-groove plate welded using LA-100 (a) transverse direction (b) longitudinal direction (c) distribution of stress free lattice spacing d_0 (d) distribution of FWHM

Fig. 3 shows the residual stress calculation result of the Y-groove plate welded using LTT filler wire HV1766. Though Fig. 3d exhibits a significant spatial variation of FWHM, the WM cannot be

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identified in the map since the FWHM of the WM and HAZ is very similar. The transverse residual stress map shows a uniform distribution of stress of 400 MPa except a slight compressive transverse residual stress the plate surface and high tensile at the bottom. For the regions which are susceptible to HIC, the transverse residual stress is below 300 MPa, which is much lower than that in the plate welded by LA-100. Fig. 3 (b) shows high compressive longitudinal residual stress in the center of the weld. Compressive residual stresses in both the transverse and longitudinal directions should be a result of the low temperature martensitic transformation of the HV1766 filler wire during cooling. For the plate welded by HV1766, the maximum longitudinal stress has a similar value and was observed at similar locations as the plate welded by LA-100. It is noted even though HV1766 could eliminate HIC when it is used to weld MIL-DTL-12560 high strength steel, high longitudinal residual stress is still observed in HAZ close to weld root. The reason of high longitudinal residual stress is not clear at this moment. The high tensile residual stress may be detrimental to the mechanical integrity of the weld, which need to be investigated in the future.

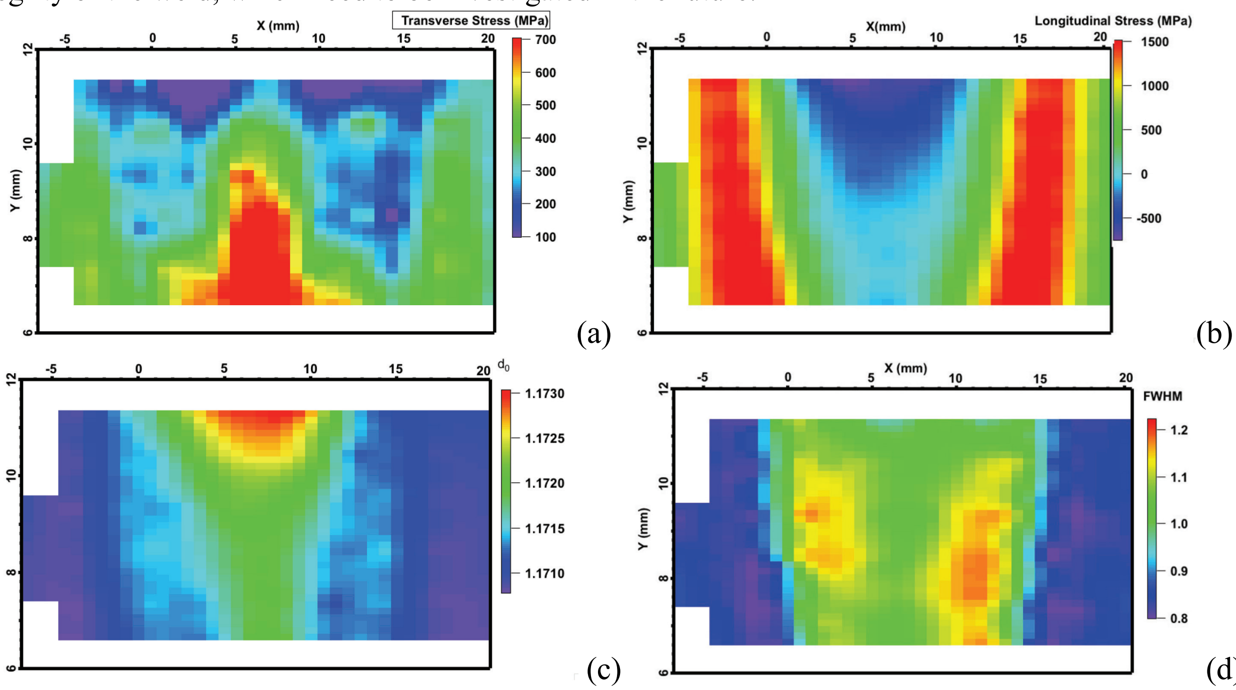

Figure 3. Residual stress distribution of Y-groove plate welded using LTT filler wire HV1766 (a) transverse direction (b) longitudinal direction (c) distribution of stress free lattice spacing d_0 (d) distribution of FWHM

Summary and Conclusions

Low temperature transformation (LTT) weld filler wires have been developed and show a reduced tensile residual stress and an improved HIC resistance. The current study used the Y-groove test to determine HIC sensitivity during welding. MIL-DTL-12560 plates were both welded by conventional ER100 (SuperArc LA-100) filler wire and LTT filler wire HV1766. A crack throughout the weld in conventional ER100 filler wire indicates ER100 is very susceptible to HIC. No crack is seen using LTT filler wire HV1766. Preliminary neutron diffraction results have shown the LTT filler wire HV1766 produced a compressive residual stress in the weld in longitudinal direction. In transverse direction, the HV1766 plates shows lower tensile residual stress compared that in ER100 plate. This lower tensile residual stress contributes to HIC resistance of LTT filler wire.

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