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Tensile overload-induced plastic deformation and fatigue behavior in weld-repaired high-strength low-alloy steel

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ABSTRACT

The effects of tensile over-load (OL) on fatigue crack growth behavior of a weld-repaired high-strength low-alloy (HSLA) steel were studied by measuring both the fatigue crack growth rate and sample-thickness variation along the fatigue crack growth path. The thickness variation, indicating the degree of plastic deformation (PD), provided an indirect measurement of associated residual compressive stresses at the crack-tip. The applied tensile OL with one-hour holding period in each test generated a damage zone at the crack tip. Microscopic details of the crack-tip damage zone were characterized by scanning electron microscopy. Three groups of expanded compact-tension (E-CT) samples, 10 mm in thickness, were tested: weld-repaired HSLA without soft buffer layer (BL), and weld-repaired HSLA with 4 mm or 10 mm thick BL. The experimental results showed that the OL-induced PD, closely linked to the crack-tip residual compressive stresses, reduced the subsequent fatigue crack growth rate, and that the HSLA with a 10 mm BL had the lowest growth rate, indicating a soft BL with an adequate thickness could further improve the fatigue resistance.

1. Introduction

Welded high-strength low-alloy (HSLA) components are widely used in automotive, transport equipment, storage tanks, excavator buckets, high-rise buildings and induced draft fans, as discussed by Mohan et al. (2002). The welded components are often operated under a spectrum of varying loads. A good understanding of fatigue behavior in welded HSLA samples tested in laboratory under different welding and structural conditions is clearly beneficial. This is because mechanisms identified to enhance fatigue resistance and fatigue lifetime can be adopted to improve the reliability and useful lifetime of those welded HSLA structures.

Many studies have been carried out to improve the fatigue properties of welded components and to minimize any detrimental effect from the associated welding processes. Prasad and Dwivedi (2008) studied the effects of welding-procedure-related parameters (welding current/voltage/speed, heat input) on the microstructure, hardness and toughness of welded HSLA steels. They found that an increase in the heat input, by changing the welding current and speed, coarsened the grain structure, thus reduced the hardness in the weld metal (WM) and the heat-affected zone (HAZ). As reported by Ohta et al. (1982), the fatigue properties of WM and HAZ of welded joints formed by different welding methods (e.g., submerged arc welding and gas metal arc welding) were inferior to those of the parent metal (PM) because of tensile residual stresses. However, Tsay et al. (1992) reported that a laser multiple-tempering process or a moderate post-weld heat-treatment (at 525 °C for one hour) could greatly improve the fatigue crack growth properties in WM and HAZ as the subsequent fatigue crack growth rate (da/dN) was similar to that of PM. The improvement in da/dN of WM and HAZ due to the adoption of laser welding was further reported by Tsay et al. (1997). Paradowska et al. (2005) reported that the residual stresses from welding process significantly altered the fatigue behavior of welding joint, e.g. high tensile residual stress reduced the fatigue performance.

To determine the effects of tensile overload (OL) and associated residual compressive stresses on fatigue crack growth in metals, single and multiple tensile OLs and subsequent fatigue behaviors have been studied by many researchers. For instance, Wheatley et al. (1999) studied the effect of single tensile OL on the fatigue behavior of 316L steel, and found that the fatigue crack growth retardation increased greatly with increases in the OL magnitude and duration. Daneshpour et al. (2009) investigated fatigue crack growth retardation induced by both single and periodic multiple OLs by using a homogenous PM and the WM extracted from a laser beam under-matched welded block. They found that the fatigue

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Nomenclature

HSLA	high-strength low-alloy
PM	parent metal
WM	weld metal
BL	buffer layer
E-CT	extended-compact tension
K	stress intensity factor (MPa $m^{1/2}$)
P	applied load (kN)
B	thickness of the sample (mm)
W	width of the sample (mm)
a	crack length from the loading line (mm)
SEM	scanning electron microscopy
OL	overload
DZ	damage zone
PDZ	plastic deformation zone
HAZ	heat-affected zone

life of the welded sample was longer than that of the PM under the single OL condition because of its larger plastic zone within the WM, but it was shorter under the multiple OLs condition because of its confined plasticity evolution within the narrow zone in the WM. In addition, multiple tensile OLs can interact with each other and thus counteract the effect of each single OL. To establish a clearer pattern of OL interactions, a number of studies have been carried out by Mills and Hertzberg (1976) and Lang and Marci (1999) to assess how OL interactions depended on the relative magnitude and spacing between OLs, and by Yildirim and Vardar (1990) and Tür and Vardar (1996) to assess the effect of OL frequency on the fatigue retardation.

The present study attempts a direct measurement of the OL-induced plastic deformation (PD) in the thickness direction along the fatigue crack growth path in there different weld-repaired HSLA samples of 10 mm in thickness, and the corresponding fatigue crack growth. Detailed features of the crack-tip damage zone (DZ) generated by the tensile OL with one-hour holding period were characterized by a scanning electron microscopy (SEM). The tensile OL-induced PD provided an indirect measurement of the associated residual compressive stresses at the crack-tip, and the positive effect of tensile OL on fatigue clearly outweighed the negative influence of DZ. The primary objective of the present study was to measure detailed OL-induced PD distributions and to see how a soft buffer layer (BL) between the WM and the PM interacts with the tensile OL. The OL-induced PD distribution along the fatigue crack path through the WM, BL and PM can provide further information on selections of suitable WM and BL for joining or weld-repairing HSLA structures. Therefore, any detrimental effect of heat-affected zone (HAZ), as discussed in Mohandas et al. (1999), can be effectively limited through proper selections of WM and BL for HSLA.

2. Experimental procedure

2.1. Materials and samples

The parent metal (PM) employed in this study was Bisplate80, a HSLA steel, which has been widely used for welded structures because of its high strength, low carbon content, and good weldability. The yield strength and ultimate tensile strength of the PM were 690 MPa and 790 MPa respectively. Two types of electrodes with different chemical compositions and mechanical properties, SmoothCor™ 115 and SmoothCor™ 70C6, were chosen as the weld metal (WM) and the buffer layer (BL), respectively. Flux cored arc welding was used for the welding repair to form three types of weld-repaired HSLA blocks with different compositions and strength characteristics. The chemical compositions and mechanical properties of the PM, WM and BL and the relevant welding parameters were reported by Zhang et al. (2012a).

The expanded compact-tension (E-CT) sample geometry was adopted in this study. All the weld-repaired HSLA E-CT samples contained machined-notches in the WM, introduced using a wire electric discharge machine, were divided into three groups: weld-repaired HSLA without BL and weld-repaired HSLA with 4 mm or 10 mm BL. Those E-CT samples had an initial notch/sample-width, a/W, ratio of 0.08, where the width W = 60 mm and the sample thickness = 10 mm.

Two samples were prepared for each group, one for constant amplitude fatigue test and the other for overload (OL) test. The first OL was applied after the fatigue crack extended up to 10 mm away from the loading line, then the corresponding OL-induced plastic deformation (PD) along the fatigue crack growth path in the thickness direction was measured.

2.2. Fatigue crack growth test and tensile over loading (OL)

All fatigue crack growth experiments were performed using a sinusoidal load function with a maximum load of 30.0 kN, R-ratio of 0, and frequency of 5 Hz. Tensile OL with one-hour holding period was applied on selected samples during OL tests. All fatigue crack growth tests were conducted in accordance with ASTM E 647 (23).

Three groups of E-CT samples were tested, and they were: (1) the weld-repaired HSLA without a BL between WM and PM, (2) the weld-repaired HSLA with a 4 mm BL, and (3) the weld-repaired HSLA with a 10 mm BL. Two identical samples for each group were tested. One sample was fatigue-tested to final failure without OL, and the other with two OLs before final failure. All those E-CT samples were tested in ambient condition using a servo-hydraulic Instron 8501 testing machine. One side of the samples was polished to facilitate optical measurement of the crack length with the aid of a traveling optical microscope attached to the Instron machine. The accuracy of the measurement of crack length was close to ±0.01 mm.

The testing procedure was as follows. A fatigue pre-crack of approximately 1 mm from the notch root was first initiated under cyclic loading with a high load amplitude of approximately 60% yield strength of the WM. Then the load was subsequently reduced to the desired load amplitude of 30.0 kN adopted in the actual fatigue test. Two tensile OL-cycles were applied on those samples selected for OL tests: (1) The 1st OL to the level of ΔK = 126 MPa $m^{1/2}$ (70 kN) was applied with one-hour holding period after the fatigue crack was extended up to approximately 10 mm away from the loading line (crack-tip was within the WM). (2) The 2nd OL to the level of ΔK = 140 MPa $m^{1/2}$ (52 kN) was applied with one-hour holding period after the crack was extended up to approximately 17.5 mm; The crack-tip was within the melted parent metal (MPM) zone created during welding for the weld-repaired HSLA without a BL, and within the region consisting of BL and MPM (BL + MPM) for the weld-repaired HSLA with 4 mm or 10 mm BL. The samples were then fatigue-tested to final failure. The fatigue crack growth data were smoothed using a four-point averaging technique.

The number of fatigue cycles, N, required for incremental crack growth was recorded, and the fatigue crack growth rate, da/dN, was calculated directly by dividing the increment of crack length, Δa, by the elapsed number of fatigue cycles. The stress intensity factor range ΔK and its variation during fatigue test for the E-CT geometry was calculated by the following equation, as shown by Piascik and Newman (1995):

$$K = \frac{(P/B\sqrt{W}) \times (2+\alpha)}{[(1-\alpha)^{3/2} \times (1-d/W)^{1/2}] \times (1.15 + 0.94\alpha - 2.48\alpha^2 + 2.95\alpha^3 - 1.24\alpha^4)} \quad (1)$$