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Fatigue and hardness effects of a thin buffer layer on the heat affected zone of a weld repaired Bisplate80

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ABSTRACT

Heat-affected zones (HAZs) in extensively weld-repaired Bisplate80, or the parent metal (PM), have been studied and examined using hardness measurements in conjunction with fatigue crack growth measurements and detailed scanning electron microscopy (SEM) observations. Three different groups of specimens have been prepared, i.e. as-received PM, weld-repaired PM with a thin 4 mm BL between PM and weld metal (WM), and weld-repaired PM without BL. The extended compact tension (E-CT) specimens for fatigue measurements are prepared according to the ASTM specifications, which are also used for hardness measurements. Hardness and fatigue crack growth variations across the boundaries between WM, BL and PM have been measured together with detailed SEM observations. It has been found that the welding process without BL reduced both hardness and fatigue resistance, especially around the weld interface and within the HAZ. Incorporation of a thin soft BL between WM and PM has increased both hardness and fatigue resistance around the weld interface and within the HAZ.

1. Introduction

Bisplate80 with a typical yield strength around 750 MPa is a commonly used high-strength low-alloy (HSLA) steel, featuring low carbon content, excellent notch toughness, good weldability and formability. It can be potentially welded to a range of different steels if welding conditions and consumables are adequately selected.

It is known that the microstructures of weld metal (WM) and parent metal (PM) undergo considerable changes because of the heating and cooling cycle of a welding process, e.g. as discussed in Gunaraj and Murugan (2002). To reveal the heat-affected zone (HAZ) around a weld, hardness measurement, metallographic and electrochemical etching techniques have been commonly used. For instance, Huang et al. (2005) investigated the HAZ in an Inconel 718 sheet using those aforementioned methods. It has been found that the hardness measurement is simple and effective as it clearly shows the hardness variations around the weld and HAZ.

A welding process usually reduces the hardness, and impairs the strength and fatigue behavior of a welded structure, especially around the welded interface and within HAZ. Mohandas et al. (1999) studied the effect of hardness reduction within HAZ in HSLA steels, and noted that the low carbon-equivalent of the steel had a positive influence on minimizing the hardness reduction within the HAZ, and it was also noted that external cooling methods, such as copper backing and argon purging, could also be used to further minimize the hardness reduction.

Yamasaki et al. (1984) evaluated the residual fatigue life of both weld- and bolt-repaired parts, and found that high residual stresses resulted from the conventional welded repair without any special treatment had significantly increased the fatigue crack growth rate. And as shown in Ravi et al. (2004, 2006), mis-match ratio, post weld heat treatment and notch location, also had significant influence on both fatigue crack initiation and propagation in a welded HSLA. Smith et al. (1997) studied the effect of a long post weld heat treatment on the microstructure and mechanical properties of a welded joint. The high heat input welding resulted in a decrease in the HAZ toughness because of the presence of upper bainite. Prasad and Dwivedi (2008) did a series of experiments with varying heat input, welding current and welding speed, and found that increase in heat input coarsened the grain structure in weld metal and HAZ while the hardness reached the peak point in the HAZ.

Tsay et al. (1992) studied the fatigue behavior of a laser-welded 4130 steel. An abnormally high fatigue crack growth rate in the weld metal and HAZ under the as-welded condition had been observed. However, the fatigue behavior was ameliorated with either laser multiple-tempering or post weld heat treatment at

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Table 1
Mechanical properties of Bisplate80 (PM), WM and BL.

Series	Tensile properties			
	Tensile strength, yield (MPa)	Tensile strength at break (MPa)	Elongation at break Min (%)	Impact energy Min (J)
PM	690 Min	790–930	18 Min	40 Min
WM	690 Min	760–840	17	30
BL	410 Min	490–600	22	27

525 °C for 1 h. Similar findings had also been reported by Ohta et al. (1982).

With a suitable thermo-mechanical control process, the fatigue crack growth rate in HAZ could be lower than that in a parent metal, as shown in Tsay et al. (1999). A bi-metal system with strength gradient weld was also studied to investigate the fatigue characteristics through a soft parent steel and a strong weld by Ukadgaonker et al. (2008). The high strength gradient across the weld interface had a retarding effect on the fatigue crack growth rate as the fatigue crack approached the stronger steel. In addition, Singh et al. (1990) studied the fatigue behavior of a HSLA in both as-received and heat treatment conditions. The quenching and tempering treatments increased the tensile strength and hardness, but decreased the fracture toughness.

Zhang et al. (2009) studied the coarse grained HAZ in HSLA structural steels. Both the Nb content and cooling rate influenced metallographic transformation significantly. Microstructure variations in a weld metal with the cooling rate were also reported by Ghosh et al. (2011). Furthermore, microstructures of the coarse-grained region of a HAZ in HSLA bainite steels were studied by Wan et al. (2010). The microstructures in the coarse-grained region of the HAZ consisted of predominantly bainite packets and a small portion of acicular ferrite, which was more stable than bainite during tempering.

In summary, those aforementioned investigations have exclusively concentrated on improving the fatigue characteristics and mechanical properties of weld metals and HAZ in parent metals by modifying the welding procedure, and pre- and post-weld heat treatments, e.g. electrode diameter, heat input, welding consumable, welding current, welding speed, arc voltage, wire feed speed, quenching and cooling rate.

The primary objective of the current investigation is to study an alternative method for improving the fatigue performance, which relies on introduction of a thin and soft buffer layer (BL) between the relatively hard parent metal (PM or Bisplate80) and weld metal (WM). The tri-metal system with different material compositions potentially can be designed to increase the fracture toughness, strength or reduce residual stresses from welding in HAZ or around the interfaces between WM and BL, and between BL and PM.

2. Experimental procedure

2.1. Material and specimen

The parent metal (PM) employed in this work was Bisplate80. Flux cored arc welding was used as the joining process for these components while CO_2 was used as the shielding gas. The weld metal (WM) and buffer layer (BL) were SmoothCor^{TM} 115 and SmoothCor^{TM} 70C6, respectively, thus effectively forming a tri-metal system together with PM with different strength characteristics and material compositions.

The as-received PM contains by weight percent 0.16 C, 1.1 Mn, 0.2 Si, 0.2 Mo, 0.03 S, 0.02 B, 0.01 P and the balance is Fe. The WM and BL contain by weight percent 0.06 C, 2.29 Ni, 1.4 Mn, 0.44 Mo, 0.3 Si, 0.22 Cr, and 0.03 C, 1.66 Mn, 0.59 Si, respectively. The mechanical properties of PM, WM and BL are listed in Table 1. Table 2 shows the flux cored arc welding parameters used in this study. Extended compact tension (E-CT, here CT is used as the compact tension geometry is well-known) specimens with through-the-thickness notches for fatigue and Vickers hardness tests were machined according to the specifications of ASTM E647 (23) (10 mm thick). Three groups of specimens were prepared: as-received PM, weld-repaired PM without BL, weld-repaired PM with a thin 4 mm BL between PM and WM. The metal blocks were then sliced and machined into the required dimensions as shown in Fig. 1. The weld metal region was centered in the gauge length of the tensile specimens as shown schematically in Fig. 1(b) and (c), and the crack length was measured from the loading line as indicated in Fig. 1(b).

Table 2
Flux cored arc welding parameters used in the study.

Welding process	Flux cored arc welding
Series	WM and BL
Electrode diameter (mm)	1.2
Welding consumable	100% CO_2
Welding current (A)	230
Arc voltage (V)	27
Electrode stick-out (mm)	20

2.2. Vickers hardness testing

A hardness survey was conducted near the fatigue crack growth path from the blunt-notch root across the WM, BL and HAZ to PM of each specimen. All hardness readings were obtained at indentation load of 20 kg-f by using Mitutoyo Hardness Tester (Model AVK-C2). The Vickers hardness distribution curves in the as-received PM and weld-repaired PM with and without BL are presented in Figs. 2–4 together with the sketches indicating their positions.

2.3. Fatigue crack growth testing

Three groups of E-CT specimens: (1) as-received PM, (2) weld-repaired PM without BL, and (3) weld-repaired PM with 4 mm BL between the WM and PM, were tested under the similar fatigue loading condition. The Paris fatigue curves for each group were measured twice with two identical specimens under the same loading condition.

The fatigue crack growth tests were performed at room temperature using hydraulic fatigue testing machine Instron 8501 with the load capacity of 100 kN. Constant amplitude tensile loads with a haversine waveform at a frequency of 5 Hz were used with the stress ratio $R = 0$ throughout the tests.

The initial fatigue pre-cracking before fatigue propagation testing was at least 1 mm from the blunt-notch root, and the total initial crack size after fatigue pre-cracking was about 5.8 mm from the loading line for all specimens. The fatigue crack growth rate da/dN of the as-received and weld-repaired PM under different welding condition using E-CT specimen was calculated as a function of stress intensity factor range ΔK. The number of fatigue cycles, N, required for failure was recorded to compare the fatigue crack propagation life of each E-CT specimen.