Journal of Materials Processing Technology 214 (2014) 229–237

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Residual stress and softening in welded high-strength low-alloy steel with a buffering layer

Chunguo Zhang[a,b,*], Pengmin Lu[a], Xiaozhi Hu[a,b]

[a] Key Laboratory of Road Construction Technology and Equipment, MOE, Chang'an University, Xi'an 710064, PR China
[b] School of Mechanical and Chemical Engineering, The University of Western Australia, Perth, WA 6009, Australia

ARTICLE INFO

Article history:
Received 5 July 2013
Received in revised form 30 August 2013
Accepted 1 September 2013
Available online xxx

Keywords:
Hardness measurement
X-ray diffraction
Steel
Welding
Residual stresses
Phase transformation

ABSTRACT

Welding residual stresses, Vickers hardness and microstructure of welded high-strength low-allow steel, known for high strength and low carbon content, were studied under the following conditions: as-received high-strength low-alloy steel, welded high-strength low-alloy steel without a buffering layer, and welded high-strength low-allow steel with various thickness buffering layer. A soft buffering layer with a modest thickness between the parent metal and the weld metal could be incorporated to welded high-strength low-alloy steel to effectively reduce the widths of tensile residual stress zone and welding softening zone, to change the residual stress (in *y*-direction) nature at the weld root from tensile to compressive, and to refine the grains of the welded high-strength low-alloy steel. The width of the tensile residual stress (in *x*-direction) zone was approximately equivalently to that of the welding softening zone for those welded high-strength low-alloy steel with and without buffering layers.

1. Introduction

High-strength low-alloy (HSLA) steels are widely used because of high yield strength, low carbon content and good weldability. However, when submitted to welding process, the mechanical properties and microstructure of weld metal and heat-affected zone (HAZ) could be easily modified as reported by Yi et al. (2011), e.g. welding softening, residual stresses and grain coarsening. Welding softening often generates low strength and poor fatigue behavior. High tensile stress leads to loss of performance in fatigue. Paradowska et al. (2005) found that restraints had important influence on residual stresses distribution of welded component, e.g. additional restraint increased the value of stresses. Wheatley et al. (1999) studied the effect of an overload on subsequent fatigue behavior in a 316L stainless steel, and found the incorporation of a tensile overload considerately increased the total fatigue life. Compressive residual stress was the main cause of fatigue crack growth retardation. Zhang et al. (2009) found that grain coarsening and precipitation in the HAZ reduced its toughness and fatigue strength.

Welding processes and cooling ways were explored by Mohandasa et al. (1999). They found that high-heat-input aggravated the welding softening in the HAZ. However, Cu backing and back purging with argon, or appropriate post-weld heat-treatment could reduce the softening. The effects of welding process parameters on microstructure, hardness and toughness were studied by Prasad and Dwivedi (2008). They found that an increase in heat input was prone to coarsen the grains of microstructure, thus reduced the hardness. Moon et al. (2011) investigated welding procedures for joining HSLA STEEL. They found that laser beam welding was more attractive than other welding processes, such as submerged arc welding and gas metal arc welding. This is because laser beam welding with concentrated heat source allows for narrow and deep weld seams as well as for fast welding speed, which results in low heat input. The improvement in fatigue behavior of welding joint due to adoption of laser welding process was also reported by Tsay et al. (1992). This is also because laser beam welding produces low heat input and concentrated heat source. Moreover, Coelho et al. (2013) further improved laser beam welding process. They reported that induction heating combined to laser welding effectively suppressed martensite formation and smoothed hardness profile of the welding joints. This is because the incorporation of induction heating expanded cooling times.

Overloading fatigue tests are often carried out to study the effects of residual stress induced by plastic deformation on fatigue behavior, and to improve fatigue performance of steels and welded components. Wheatley et al. (1999) studied the effects of single tensile overload on fatigue crack growth rate (da/dN) of 316L steel. They found that the da/dN retardation increased with increase in

* Corresponding author at: Chang'an University, Nan Er Huan Zhong Duan, Xi'an 710064, PR China. Tel.: +86 29 8233 4482; fax: +86 29 8233 4482.
E-mail addresses: zcguo2008@163.com (C. Zhang), lpmin@chd.edu.cn (P. Lu), xhu@mech.uwa.edu.au (X. Hu).

0924-0136/$ – see front matter
http://dx.doi.org/10.1016/j.jmatprotec.2013.09.002

Nomenclature

HSLA	high-strength low-alloy
PM	parent metal
WM	weld metal
BL	buffering layer
MPM	melted parent metal
BL + MPM	a mixture of the BL and the MPM
E-CT	extended-compact tension
RS	residual stress
HAZ	heat-affected zone

the overload magnitude and duration. This indicated that larger overload could produce larger compressive residual stress. Investigation of multiple overloading fatigue tests was carried out by Yuen and Taheri (2006). The incorporation of multiple tensile overloads could either enhance or reduce overall fatigue life depending on their magnitudes, spacing between the overloads, and the applied frequency. Daneshpour et al. (2009) further studied the influence of overload during constant amplitude fatigue test. They found that the influence of overload(s) on fatigue behavior was also closely related to the yield strength of tested materials.

The present study built on preliminary results reported in earlier work, as shown in Zhang et al. (2013). The paper reported measurements of residual stress-induced deformation and corresponding fatigue behavior of welded HSLA steels with and without buffering layer (BL), and provides a qualitative analysis on the welding residual stresses according to the calculated results of released residual stress. The primary purposes of the present investigation were to improve residual stress distribution of the welded HSLA steel by incorporating a BL, to quantitative study the residual stress distribution, and to propose the relationship between the width of tensile residual stress zone and the width of welding softening.

2. Experimental procedure

2.1. Materials and samples

The parent metal (PM) used in this study was Bisplate80, an HSLA steel. SmoothCor™ 70C6 with even strength as compare with the PM was chose as a weld metal (WM) to form a match welding joint: welded HSLA (PM + WM), which was taken as a reference base. A softer metal as compared with the PM had a stress buffering effect to reduce cold crack during welding process. The softer layer (SmoothCor™ 115) was introduced between the PM and the WM, and was designated as buffering layer (BL). A repair weld is that wear damaged section is repaired or filled by metal(s) through welding. This study is relevant since wear damaged sections of supporting structures manufactured from HSLA steel are often repaired or filled by metal with even or higher strength as compare with PM through welding, as reported by Scholl et al. (1990). The mechanical properties and chemical compositions of the PM, the WM and the BL are shown in Table 1.

As shown in Fig. 1, block of as-received HSLA steel with semi-circle notch was filled by WM (or by WM and BL) using a flux cored arc welding process while CO_2 was used as the shielding gas. Welding procedure parameters for both the WM and the BL were as follows: electrode diameter = 1.2 mm, welding current = 230 A, arc voltage = 27 V, and electrode stick-out = 20 mm. The weld-blocks were then sliced and machined into the required dimensions of expanded compact-tension (E-CT) sample geometry with a machined U-notch in the PM. Details of as-received HSLA and welded HSLA E-CT samples with and without BLs are shown in Fig. 2, and the E-CT sample thickness = 10 mm. The width of HAZ in the welded HSLA steel without a BL was approximately 5 mm. This indicated that welding process could influence the material properties of the substrate metal in certain width. Two kinds of thickness BLs were selected in this study to account for the influence. One thickness of 4 mm was selected to ensure that the whole BL zone could be influenced by the subsequent heat input resulted from WM welding. The other thickness of 10 mm was selected to ensure that not the whole BL zone was influenced by the subsequent WM welding. There were four groups of samples: as-received HSLA (PM), welded HSLA without a BL, and welded HSLA with 4 mm or 10 mm BLs.

2.2. Vickers hardness (VH) distribution

The hardness profiles of the PM and the welded HSLAs with and without BLs were tested with an indenting load of 20 kg by using a Mitutoyo AVK-C2 Hardness Tester (Akashi Corporation). The Vickers hardness (VH) was measured by moving across first the PM, then the heat-affected zone (HAZ), then the melted parent metal (MPM) for the welded HSLA without a BL or the mixture of BL and MPM (BL + MPM) for the welded HSLA with a BL, and finally the WM.

2.3. Residual stress (RS) measurement

Residual stress (RS) measurement was carried out with X-350A X-ray stress analyzer using the ψ-technique and the α-Fe_{211} diffraction. A Cr-K_α-laboratory source was used with a beam size diameter of 1.5 mm. The stress value was given by the gradient of a plot of diffraction angle 2θ against $\sin^2 \psi$, where ψ was the angle between the diffracting planes and the specimen surface. RS profiles were measured across the sample surfaces of the welded HSLA with or without BLs, over the regions of WM, MPM or BL + MPM, HAZ and PM, covering the entire width of the samples. Because of the limitation of penetrability of X-ray diffraction, the value of measuring stress was an average stress value from the sample surface to the depth of tens of microns. Because the X-ray diffraction method cannot measure stresses normal to the specimen surface, the stresses were only determined in the other two directions using a ψ-range of 0–45°. Prior to the measurement of RS, the surfaces of the welded HSLA with and without BLs were cleaned with ethanol. To remove the surface hardening resulted from wire-electrode cutting, the spots for RS testing were electro polished to a certain depth using an electro polishing kit with sodium chloride solution. To minimize the effects of chemical polishing on the stiffness and boundary conditions of welding joints, the chemical polishing should not be too deep. In this study, tested spots were polished to the depth of approximately 0.2 mm.

Table 1
Mechanical properties (min) and chemical compositions (wt.%) of the PM, the WM and the BL.

Item	YS Mpa	TS Mpa	E (%)	C	Si	Mn	Cr	Mo	Ni	P	S	B
PM	690	790	18	0.18	0.20	1.40	0.20	0.20	–	0.01	0.003	0.001
WM	690	760	17	0.06	0.30	1.40	0.22	0.44	2.29	–	–	–
BL	410	490	22	0.03	0.59	1.59	–	–	–	–	–	–

Yield strength – YS, tensile strength – TS, elongation – E.