Materials Science & Engineering A 698 (2017) 341–347

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

The effect of strain strengthening on the mixed mode crack fatigue propagation in the HAZ of 06Cr19Ni10 stainless steel

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ARTICLE INFO

Keywords:
Mixed mode fatigue crack propagation
HAZ
Strain strengthening

ABSTRACT

The present study focuses on the mixed mode fatigue crack propagation in the HAZ of 06Cr19Ni10 stainless steel. The effects of strain strengthening on crack growth path, crack growth rate, residual stress and microstructures were analyzed separately. The results of crack propagation test show that a new fatigue crack initiated from pre-crack tip and propagated along a line perpendicular to the loading direction. It is noted that strain-strengthening could reduce the crack growth rate but it has no effect on crack propagation path. Strain strengthening can produce stress-induced martensite and the martensite volume fraction increases with the strain-strengthening level. Finite simulation analysis and experiment results show that residual tensile stresses of HAZ can be reduced significantly by strain-strengthening treatment.

1. Introduction

Strain-strengthening technology has been used to improve the yield strength of austenitic stainless steel in aerospace, pressure vessel and energy industries [1]. Welding processes such as metal inert gas (MIG), submerged arc welding (SAW) and tungsten inert gas (TIG) are widely applied to fabricate welded structures. Generally, a welding joint comprises of three regions: the weld zone, the base metal zone and the heat affected zone (HAZ). Due to low mechanical properties and inhomogeneous microstructure, HAZ is considered as a brittle zone where cracks and defects are easily to be found. Many researchers investigated the effect of strain strengthening on the fatigue behavior of base metal. However, few studies focus on the fatigue behavior of the HAZ. Therefore, the effects of strain strengthening on the mechanical performance in HAZ of 06Cr19Ni10 austenitic stainless steel need to be investigated.

Robertson et al. [2] studied the effect of strain strengthening on the fatigue properties of TRIP steel. They found that strain strengthening can increase the tensile stress and the elastic-plastic strain ratio of material. Tang et al. [3] studied effect of strain strengthening on microstructure and properties of TRIP steel. They found that the volume fraction of austenite decreased with the increase of prestrain. Trudel et al. [4] investigated the fatigue crack growth behavior in heat affected zone (HAZ) of CA6NM welded joint. Effects of the post weld heat treatment were also studied. They found that fatigue behavior of HAZ was similar to that of base metal when $R = 0.7$. However, when $R = 0.1$, crack growth resistance of HAZ was relatively lower and the post weld heat treatment had a beneficial effect by improving residual stress distribution.

Kim et al. [5] investigated the fatigue properties in heat affected zone of HSB800 high-performance steel. The results showed that the fatigue crack growth rate in coarse-grain heat affected zone was relatively larger than that in fine-grained heat affected zone. Xiong et al. [6] studied effected effects of acicular ferrite on crack propagation in HAZ of low carbon steel. They found that acicular ferrite impeded fatigue crack propagation and increases the length of plastic zone at the tip of the main crack. Han et al. [7] focused on the effect of precipitate type on the fatigue properties in the HAZ of 18% Cr stainless steel. The results indicated that due to the decrease of Nb contend and the coarsening of MC precipitates, the fatigue properties of HAZ deteriorated. Sillapasa et al. [8] studied tensile and fatigue properties of HAZ in friction stir welded joint of 6N01 aluminum plate. The results shown that fatigue failure appeared in the HAZ of aluminum welding joint. Tensile strength and fatigue strength were lower in HAZ.

Mcdaniels et al. [9] investigated the effects of the HAZ in AISI 4340 steel on high-cycle fatigue behavior. They found that the HAZ did not have an detrimental effect on the high-cycle fatigue behavior of AISI 4340 steel. Vargas-Arista et al. [10] analyzed the fractography and mechanical behavior of fatigue crack propagation in the HAZ of AISI 4140 steel. The results revealed that coarse grain improved the fatigue

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http://dx.doi.org/10.1016/j.msea.2017.05.051
Received 11 February 2017; Received in revised form 16 April 2017; Accepted 12 May 2017
Available online 18 May 2017
0921-5093/

Table 1
Chemical composition of base metal and welding filler (wt%).

Material	C	Si	Mn	Cr	Ni	S	P	Fe
Base metal (06Cr19Ni10)	0.045	0.45	1.10	17.1	8.00	0.001	0.028	Remainder
Filler(ER308L)	0.03	0.60	1.80	20.0	10.0	0.008	0.015	Remainder

Table 2
Welding parameters of the MIG welding process.

Parameter name	Value
Welding voltage (volts)	24.5
Welding current (amperes)	217
Welding speed (cm/min)	40
Filler material	ER308L
Welding electrode diameter (mm)	1.2
Shielding gas type	Argon (97%), O_2 (3%)
Shielding gas flow rate (L/min)	20

crack growth rate and large grain induced low fatigue resistance of HAZ. He et al. [11] estimated the fatigue lives of low-alloy steel in HAZ and fusion zone. They found that the crack initiation process occupied up to 99% of the total fatigue life. A nonlinear fatigue model which could described fatigue damage of HAZ was also developed. Bussu et al. [12] investigated the effects of residual stress and HAZ on the fatigue propagation in T351 aluminum joint. The results indicated that the weld residual stress dominated the crack growth behavior in HAZ of aluminum joint. Wang et al. [13] evaluated the low cycle fatigue damage of HAZ using continuum damage mechanics. They found the derived continuum damage model was consistence with the experimental models. Kim et al. [14] tested the effects of microstructure on fatigue crack growth behavior in HAZ of P92 welding joint. The results showed that crack growth rate of HAZ was faster that of weld metal and base metal. Wang et al. [15] studied the fatigue behavior of Q & P980 welding joints using metallographic, tensile and fatigue tests. They found that the fatigue cracks appeared in HAZ and the fagitue properties of spot weld was indenpendent of base metal. Tang et al. [16] investigated the strain-strengthening effect on mixed-mode fatigue propagation in base metal of austenite stainless steel. The results shown that the moderate fraction of martensite could be beneficial to increase fatigue life.

From the view point of material science, the mechanisms of strain strengthening are based on residual stress, phase transformation and dislocation structure.

Change of residual stress distribution introduced by strain strengthening is considered to be one of the main factors of improvement in material fatigue performance. For example, decrease in tensile residual stress and introduction of compressive residual stress will reduce the maximum tensile stress during cyclic loading, which will eventually increase fatigue properties of material [17–19].

06Cr19Ni10 stainless steel is a kind of metastable austenitic steel which has been widely used in pressure vessel industry [20]. In the present study, the fatigue crack propagation in the HAZ of 06Cr19Ni10 austenite stainless steel was investigated thorough fatigues tests.

Moreover, in order to understand the mechanism of the strain strengthening, microstructure analysis, residual stress simulation and measurement were carried out.

2. Experimental procedures

2.1. specimen preparation

The hot-rolled plates of 06Cr19Ni10 stainless steel were machined into the required dimensions (98 mm × 48 mm × 6 mm). Metal inert gas (MIG) welding technology was performed to fabricate butt welding joints. The chemical components (wt%) of investigated base metal and filler are shown in Table 1. Table 2 presents welding parameters used in this paper.

After welding, pre-pull treatments were prepared along the transverse direction of welding to get four groups of strain-strengthened specimens. The pre-strain levels of strain-strengthened specimens are 3%, 6%, 9%, 12%, respectively.

Afterward, an incline cracks were processed in the HAZ of strain-strengthened specimens by electrical-discharge machining (EDM). As presented in Fig. 1, the processed crack has a length of 6 mm and β indicates the angle from the loading direction to the incline crack.

2.2. Fatigue testing

To study the effects of strain strengthening on fatigue crack propagation in the HAZ, the fatigue specimens were divided into five groups according to different strain-strengthening levels: non-strain-strengthening (NSS) group, 3% strain-strengthening(3% SS) group, 6% strain-strengthening(6% SS) group, 9% strain-strengthening(9% SS) group and 12% strain-strengthening(12% SS) group. Different groups of specimens were tested at ambient temperature under the same fatigue loading condition. The Paris fatigue curves for each group were measured to calculate fatigue lives of specimens.

An INSTRON 8800 fatigue testing machine was employed to carry out the fatigue crack propagation tests. Constant amplitude loading with a stress ratio of 0.1 and a frequency of 15 Hz was used. A digital microscope system (Scalar DG-3) was used to monitor and record the crack length during fatigue tests.

Normally, the stress intensity factor range ΔK is used to predict the fatigue crack state. For a slanted crack in a biaxial stress field with stress σ , the mode I Stress intensity factor range ΔK_I and Mode II stress intensity factor range ΔK_{II} are both functions that depend on the slanted angle β.

2.3. Numerical simulation of residual stress

A 3D finite element model of the butt welded joint was established to perform the residual stress simulation with the popular finite element software, Marc. Effect of strain-strengthening on residual stress dis-

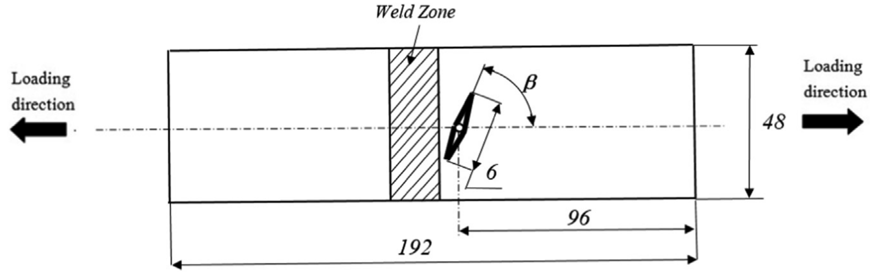

Fig. 1. Center-cracked fatigue specimen (mm).