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Research Article

Behaviour in welded heat affected zone (HAZ) of low Alloy steel

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Abstract

The behaviour of fatigue crack growth at room temperature was gotten from 4140 parent steel. The parent steel was heat treated, as-welded and material under R", 0 constant amplitude loading and single tensile overloads with an over load ratio of 2.5. The purpose of this research is to contribute to the needed information for safe design and service life of weldments, subjected to both constant amplitude and single tensile overloads. The data are essentially log-log linear and hence satisfy the region II Paris equation, the overload cycles to failure for a given *R* ratio fell within a factor of about 3.0 or less for all material test conditions, this again is a rather small variation between materials. The number of cycles of retardation, *NR,* varies from about 3.0 x 110 to 5.0 x 110 cycles. This represents fatigue crack growth life increases from about 300 to 500% for *R* ≈ 0. This indicates that all the material conditions investigated responded favorably to the single tensile overloads. All four material conditions had the same constant amplitude fatigue crack growth resistance in the Paris log-log linear region. Differences in fatigue life and fatigue crack growth rates were within a factor or two.

Keywords: Crack, Steel, Growth, Fractograph, Low Alloy Steel, Heat Affected Zone (HAZ)

INTRODUCTION

Very little fatigue crack growth retardation information exists for weldments. Therefore, the purpose of this search is to contribute to the needed information for safe design and service life of weldments, subjected to both constant amplitude and single tensile overloads. This contribution is achieved using 4140 steel evaluated by fatigue testing and scanning electron microscopy (SEM).

A weldment is a very complicated and variable structure formed from different thermal and environmental conditions (Phillip, 2003; Frost et. al., 2001). These complexities involve inherent mechanical behavior such as strength, ductility, hardness and fracture toughness. In addition, three dimensional residual stress/strain can result in significant decrease of fracture toughness. (Kameda et al., 2006; Dawes, 2006).

Both high and low amplitude cycles along with constant amplitude cycles can occur in welded structures and components. Hence sequence, or interaction effects, is of importance in calculating fatigue crack growth life of weldments. High tensile overloads followed by low amplitude loading can involve appreciable retardation of fatigue crack growth. This retardation has been attributed to crack tip blunting, residual compressive stresses in front of the crack tip and to crack closure. In order to better calculate fatigue crack growth life in weldments, this retardation influence must be known quantitatively.

Most welded structures and components are subjected to variable amplitude loading. Initial cracks can then grow under cyclic load to fracture. Both high and low amplitude cycles along with constant amplitude cycles can occur in welded structures and components. Hence sequence, or interaction effects, is of importance in calculating fatigue crack growth life of weldments. High tensile overloads followed by low amplitude loading can involve appreciable retardation of fatigue crack growth. This retardation has been attributed to crack tip blunting, residual compressive stresses in front of the crack tip and to crack closure.

In order to better calculate fatigue crack growth life in weldments, this retardation influence must be known quantitatively. Very high post weld heat treatment, over 7000e, of these steels, however, can cause a coarse grained region near the fusion line of the Hal resulting not only in embrittlement, but also in stress relief cracking (Hippsley et al., 2000). Lim (Lim and Chung, 2008), using COD fracture toughness and fracture surface observations, showed that the degree of post weld heat treatment embrittlement is dependent upon heating rate, holding time, applied stress and grain size of the weld microstructure.

Design and research against unstable brittle fracture of welded structures and components is an active international problem (McHenry et al., 2008), Brittle fracture of welded structures often starts from the heat affected zone (Dolby, 2002; Burdekin, 2007). Therefore, in welding low alloy steels such as 4140, post weld heat treatment is a common practice for removing undesirable residual tensile stresses along with welding and reheat for repairing (Suzuki et al., 2006; Bloom, 2001).

METHOD

Amplitude tests were obtained with load ratio, $R = Pmin / Pmax$, of approximately zero using a positive haversine wave with a frequency of 30 to 35Hz. The amplitude data ranged from 10^{-8} to $1O^{-6}$m/cycle and were in region II or the Paris log-log linear region. Single tensile overloads were applied at a crack length of 30mm with an overload ratio of 3.0. Overloads were applied with a ramp wave at 0.130Hz. Tests were terminated when the uncracked ligament of the *specimen (w-a)* ceased to be predominately elastic and when the crack growth rate became too great to accurately measure crack length. These criteria were essentially at about fracture. All fatigue specimens were precracked approximately 3mm to a total crack length of 23mm.

The reduction of *Pmax* between load steps was less than 25%. The maximum stress intensity factor, *Kmax* just prior to overload was 23.5 MPa $\sqrt{m}$ and the overload stress intensity factor, *Kol* , was 59 MPa $\sqrt{m}$. Crack length, a, versus applied cycles, *N,* data were reduced to *da/dN* versus *ΔK* using a second order in· cremental polynomial method for constant amplitude tests and a secant method for single overload tests.

Steel plate with 25mm thickness was cut to 153 x 620mm sections and a U shaped groove, 620mm long, was cut perpendicular to the rolled direction. The U groove was then welded using an automatic submerged arc welder with two passes. The electrode used was AWS EN2 and the flux was AWS F9A6.

The deposit metal appears as typical dendrite structure and the weld HAl is located vertically for satisfactory extraction of CT specimens.

The chevron notched specimens with *H* /*W* = 0.6 were machined so that the fatigue crack would grow through the weld HAZ fusion line parallel to the weld direction and perpendicular to the rolled direction. Specifically, single tensile overload influence on constant amplitude loading was obtained under four material conditions as follows; parent material, heat treated parent material, as-welded HAZ material and post weld heat treatment HAZ material. Heat treatment was performed on both welded and parent material CT specimens as follows; heating rate = 230^0C/hr, heating temperature = 660^0C, hold time= 1hr, cooling rate = 120^0C /hr. All fatigue tests were performed at room temperature using a closed-loop electrohydraulic test system in load control. One side of each specimen was polished in the crack growth region with progressively finer emery paper to 610 girt. Cracks were monitored on this polished surface using a 33x traveling microscope with stroboscopic illumination. Cracks were also occasionally monitored on the back side of the specimen to determine possible crack tip eccentricity during testing.

RESULTS AND DISCUSSIONS

The constant amplitude and single tensile overload crack length, a, versus applied cycles, *N,* curves for all $R \approx 0$ tests. Since each constant amplitude test started at a = 23mm and each single tensile overload test had the same overload applied at a = 30mm, followed by the same Pmax value, this provides substantial comparative results without reverting to *da/dN* versus Δ*K* curves.

The constant amplitude data are represented by open data points and labeled no overload, and the overload data are represented by solid data points or crosses within the symbol. Also for a given material condition, data points with the same shape are used for the constant amplitude test and for the overload test. These selections make for easier comparison.

The retardation cycles, *N* is the horizontal displacement of the “a” versus *N* curve following a single tensile overload. The constant amplitude fatigue crack growth curves were smooth and continuous and varied by a factor of only two or less at fracture for the given material conditions. This is a very small variation. Fatigue life is increasing the order as follows, parent, heat treated parent and as-weld at the no overload, that is, fatigue life of parent is increasing after heat treatment, but that of the welded HAZ is opposite. At single overload, all materials are retardation of crack propagation. Retardation of as-weld is the greatest. *Da/dN* versus Δ*K* curves for all constant amplitude tests using the incremental second order polynomial method.

The data are essentially log-log linear and hence satisfy the region II Paris equation, the overload cycles to failure for a given *R* ratio fell within a factor of about 3.0 or less for all material test conditions, this again is a rather small variation between materials. The number of cycles of retardation, *NR* , varies from about 3.0 x 110 to 5.0 x 110cycles. This represents fatigue crack growth life increases from about 300 to 500% for $R \approx 0$. This indicates that all the material conditions investigated responded favorably to the single tensile overloads. The as-welded HAZ material with its higher strength had the greatest response to the single overloads compared to the other lower strength materials. This difference in retardation with strength agrees with results by others (Njus et al., 2007; Petrak et al., 2009). However, the differences in fatigue crack growth for the as-welded HAZ versus the other materials must also incorporate residual stresses that have not been relaxed through post weld heat treatment. In fact, as-welded HAZ material and post weld heat treatment HAZ material have the same microstructure, but differ essentially in residual stress. Thus both strength and residual stresses are involved with the fatigue crack growth retardation.

The "a" versus *N* data for all tests were reduced to *da/dN* versus Δ*K.* Typical results for the no overload and overload conditions are shown in Fig.6 for the 'parent metal. Crack growth rates prior to the single tensile overload were above $l0^{-8}$m/cycle while after the single overload the rate dropped to almost 10^{-9}m/ cycle. Converging of the no overload and overload data occurs as the crack grows out of the effective overload region. A superposition of no over load and overload data are similar for all materials. Open data points represent no overload behavior. Greater scatter exists for the $R \approx 0$ tests, however all material tests again exhibit similar behavior. Since crack closure was not monitored in these tests, an effective Δ*K* analysis cannot be made.

Scanning Electron Microscopy (SEM)

Typical SEM fractographs for the amplitude tests with the parent, as-welded HAZ and post weld heat treatment conditions. Two magnifications are shown for each material condition. The direction of fatigue crack growth is from bottom to top in all fractographs. Very few distinct striations were evident on any of the surfaces, however so-called ductile quasi-striation crack growth morphology existed.

All materials showed porosity, inclusions and secondary cracking, and appeared rather similar except the as welded and post weld heat treatment material had more debris, more microcracks and greater roughness. Again two magnifications are used for each material condition. The upper fractographs, taken at 100x or 200x magnification, show the tensile overload markings. The lower fractographs show the fracture surface at 100 x magnification after the overload was applied. Substantial crack closure following the overload often tended to obscure some of the fatigue crack growth markings.

In general, no great differences in the fatigue crack growth morphology existed between the different materials conditions tested. This is consistent with the lack of substantial differences between material conditions.

Macrofractography

We have a typical macro fracture surfaces for the constant amplitude test and for the single overload tests. Three regions labeled *A-C* were utilized. Label *A* indicates the precrack region and boundary, Label *B* denotes the fatigue crack growth test region and label C represents the final ductile fracture region. In all cases, the fatigue cracks initiated at the chevron and grew toward the top of the fractographs. In all cases, the constant amplitude fatigue crack growth regions are rather smooth. The single overload fracture surfaces indicate the overload marks are more intense. The overload crack tip curvature is somewhat eccentric; however, the curvature still satisfied ASTM E 647 requirements. The overloads markings indicate a small difference in the 30mm crack length at overload existed. This was not a significant factor however

SUMMARY AND CONCLUSIONS

The following information is based upon room temperature fatigue crack growth and SEM investigations of the 4140 parent material, parent heat treated material, as-welded HAZ material using automatic submerged arc welding and parent heat treated material HAZ material subjected to constant amplitude loading, no-overload and single tensile overloads using an OLR of 3.0.

(1) SEM results indicated many similarities in fatigue crack growth morphology for the four material systems. Ductile quasi-striations, porosity, inclusions and secondary cracking were evident with all four material conditions. The principal differences were the greater amounts of debris, microcracks and roughness in the as-welded and parent heat treated material HAZ materials.

(2) Retardation of fatigue crack growth varied from 3.0 X $l0^5$ to 5.0 X 10^5 cycles for the four material conditions which represented an increase in fatigue crack growth life from 300 to 450 percent. The greatest retardation response occurred in the as-welded HAZ material.

(3) All four material conditions responded favorably to the single tensile overloads. The differences between material responses for theses single overloads were small, within a factor of 3.0.

(4) All four material conditions had essentially the same constant amplitude fatigue crack growth resistance in the Paris log-log linear region. Differences in fatigue life and fatigue crack growth rates were within a factor or two.

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