Mechanics of Materials 100 (2016) 198–208

Contents lists available at ScienceDirect

Mechanics of Materials

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

Failure mechanisms and fatigue strength assessment of a low strength Cr–Ni–Mo–V steel welded joint: Coupled frequency and size effects

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A R T I C L E I N F O

Article history:
Received 3 March 2016
Revised 14 June 2016
Available online 29 June 2016

Keywords:
Very high cycle fatigue
Welded joint
Size effect
Fine granular area
Fatigue strength assessment

A B S T R A C T

Axially loaded push-pull tests of a low strength Cr–Ni–Mo–V steel welds using cross-weld specimens with different sizes were conducted up to the very high cycle fatigue regime under ultrasonic frequency. Results showed that smaller samples had higher fatigue strength with interior cracking predominant at the weld metal. Fine granular area characteristic of polycrystalline features close to micro-defects was indicative of higher fatigue strength with implications of cyclic hardening, and was related to localization of plastic deformation. A physical criterion for formation of fine granular area was proposed as the ratio of accumulation to release rates of cyclic plastic energy was higher than one. It was found that the size effect on fatigue strength of the low strength welds was coupled with frequency effect, an issue that both current deterministic and probabilistic approaches were unable to rationalize, was actually dependent on tensile strength as well as extrinsic factors such as cyclic hardening and micro-defect distribution.

1. Introduction

Fatigue and fracture are size dependent (Bažant, 1984; Sih and Chao, 1984). The size effect on fatigue behavior has been reported in both notched (Lukás et al., 1989; Ren and Nicholas, 2003) and smooth specimens (Shirani and Härkegård, 2011). For axially loaded smooth specimens, a nominal stress gradient does not exist over the cross section, resulting in less size effect than in bending. In cases of bending and axial loadings, larger specimens have an increased probability of microstructural discontinuities that prompt crack initiation, and thus reduce fatigue resistance (Stephens et al., 2000). Recently, higher fatigue strength in smaller specimens under axial loading has been observed in very high cycle fatigue (VHCF) regime (Furuya, 2008; Furuya, 2011) where cracking is often originated from interior micro-defects (Sakai et al., 2015). The size effect on VHCF behavior is critical to the understanding of fatigue damage mechanisms, and in particular, to the design of a proper specimen size for fatigue testing that can truly represent fatigue properties of engineering materials (Paolino et al., 2014).

Several approaches have been established for the size effect during the past several decades. The size effect in low cycle fatigue (LCF) regime where surface crack initiation dominates is often related to surface layer size. The deterministic method developed by Murakami (2002) and probabilistic approach such as the weakest link concept (Flaceliere and Morel, 2004; Karolczuk and Palin-Luc, 2013), both of which based on the distribution of micro-defects, have been utilized for the size effect on fatigue strength in case of interior crack nucleation (Cova et al., 2014; Shirani and Härkegård, 2011). Carpinteri et al., (2009) proposed a fractal approach to size effect by considering the fractal nature of reacting cross-sections of loading structures. Nevertheless, fatigue strength in the VHCF regime is found to be significantly dependent on extra factors such as frequency (Zhu et al., 2015), where the fine granular area (FGA) was observed around micro-defects for the first time in low strength welded joints under ultrasonic frequency in our previous work. It appears that an accurate evaluation of fatigue strength requires the understanding of coupling effects of frequency and specimen size when the lower strength welds are cyclically tested under ultrasonic frequency. Although the formation of FGA is frequency dependent for strain-rate sensitive materials in the VHCF regime, its role in the size effect of fatigue strength is not clear. This sparks great interests in revisiting mechanisms for FGA that has been observed mainly in high strength steels before.

Therefore, in the present work, fatigue tests of a low strength Cr–Ni–Mo–V steel welded joints up to the VHCF regime were carried out using different specimen sizes under ultrasonic frequency. A follow-up discussion on the size effect of VHCF behavior including cracking behavior and applicability of current micro-defect based approaches were reported. Special emphasis was laid on controlling factors and mechanisms for FGA formation and its role in underlying mechanisms for size effect in low strength steels.

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http://dx.doi.org/10.1016/j.mechmat.2016.06.017
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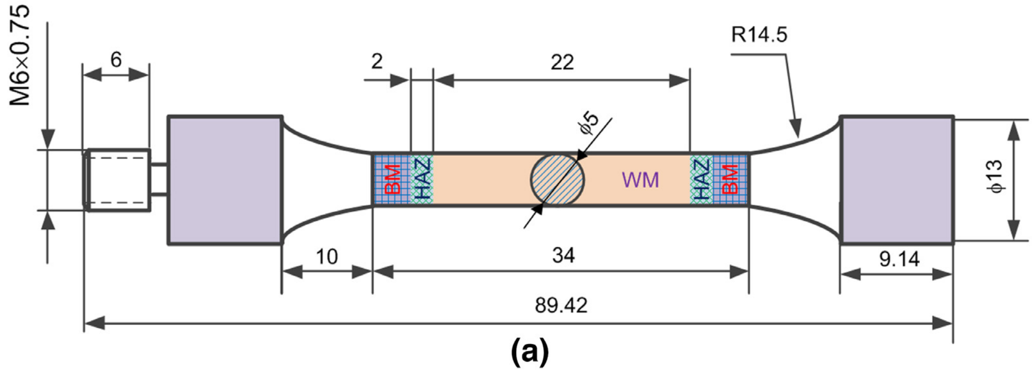

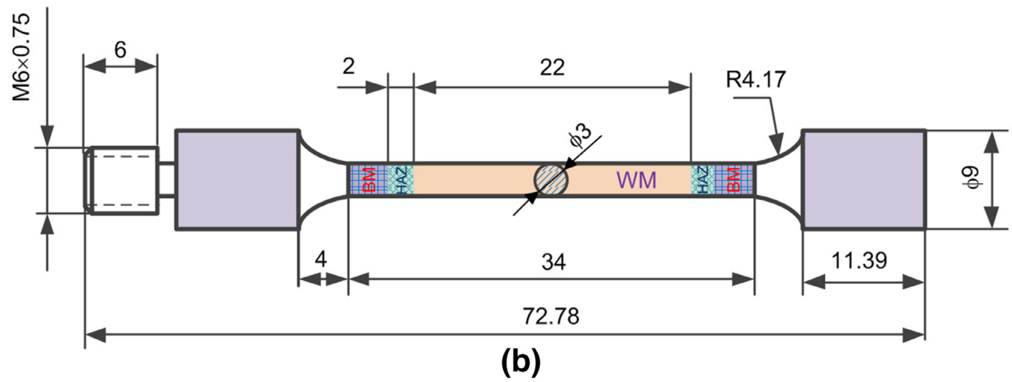

Fig. 1. Shape and dimensions of VHCF specimens at d of 5 mm (a) and 3 mm (b) (dimensions in mm).

2. Materials and experimental methods

2.1. Materials

The material investigated was a 25Cr2Ni2MoV steel welded joint, which was welded by the submerged arc welding (SAW) technique using a WM rich of Ni (Zhu and Xuan, 2015). After the SAW process, a post weld heat treatment (PWHT) under furnace cooling was carried out at 580 °C for 10 hours to reduce the welding residual stress. The room temperature yield strength (YS) and ultimate tensile strength (UTS) of the welded joint after the PWHT are 726 MPa and 778 MPa, respectively. The microstructures of the WM mainly contain tempered bainites with long and lathy shape, while microstructures in the forged BM are lathy tempered martensites. The HAZ shows a combined tempered martensite and bainites, and has been subdivided into three sub-zones according to the distribution of microstructures. A detailed characterization of microstructures and strength distribution along the welds has been reported in our previous paper (Zhu and Xuan, 2015).

2.2. Fatigue testing methods

As shown in Fig. 1, cross-weld specimens for VHCF testing were machined from the welded joint. It is noted that the parallel section part has equal diameter with a total length of 34 mm, which covers the whole WM, HAZ, and part of BM. The parallel part of the specimen is the highly stressed zone, and ideally, fracture can equally occur in each sub-zone. Specimens with different diameters, i.e., $d = 5$ and 3 mm, were chosen for the VHCF tests.

Fatigue tests were conducted in ambient environment at 20 kHz on an ultrasonic fatigue machine (USF-2000, Shimadzu, Japan) for up to a lifetime of 10^9 cycles. Prior to testing, all specimens were mechanically polished. The final surface roughness of the specimen, R_a, is lower than 0.2 μm. A sine type cyclic load with a load ratio of −1 was applied in the tests. During the tests, compressive air was used to cool the specimen. In addition, an intermittent loading scheme, i.e., 500 ms of pulse followed by 1000 ms of pause, was employed to minimize the thermal effect.

2.3. Fractography

After fatigue testing, fracture location was identified with the help of optical microscopy, and its distance to weld centerline was measured. All fracture surfaces of failed specimens were observed by scanning electron microscopy (SEM) for crack initiation analysis. Some specimens failed at internal micro-defects at the VHCF regime were selected for observation of dislocation and substructures. A rectangular area of about $24 \times 24\ \mu m^2$ around the micro-defects was cut by focused iron beam (FIB) under vacuum environment. A smaller size of the milled specimen, i.e., $6.5 \times 6.5\ \mu m^2$, fixed within mini-clamps with a layer of platinum protecting the free surface from damage, was finally prepared for observation by transmission electron microscopy (TEM).

3. Results

3.1. S–N curves

Fig. 2 shows the S–N curves of the welds. It is observed that with the decrease of stress amplitude, σ_a, the fatigue lifetime, N_f, increases gradually, indicating a continuously decreasing S–N curve for both the specimen size. By comparing with the results reported before at 110 Hz (Zhu et al., 2015), the current work further verifies that under ultrasonic testing, the S–N curve of the cross-weld specimens often shows a continuously decreasing mode. In Fig. 2, the fatigue strength for $d = 3$ mm is higher than that for $d = 5$ mm.