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Fatigue damage evaluation of low-alloy steel welded joints in fusion zone and heat affected zone based on frequency response changes in gigacycle fatigue

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ABSTRACT

The fatigue crack propagation lives of low alloy steel in the heat affected zone (HAZ) and fusion zone (FZ) were estimated based on the frequency response changes in ultrasonic fatigue, which varied with the crack size during fatigue. Results showed that more than 99% of the total fatigue life was occupied by the crack initiation process for HAZ in gigacycle fatigue. However, this number was scattered for FZ specimen owing to the crack propagation from welding defects directly. A nonlinear fatigue model based on natural frequency changes was developed, which described fatigue damage for HAZ and FZ specimens successfully.

1. Introduction

In the applications of aircrafts, automobiles, off-shore structures and railway equipments, many components with welded joints would experience nominal vibratory stresses over a long period of time, i.e. underwent several hundred million cycles and fatigue failure often occurred in their working service [1,2]. Based on statistics, the fatigue failure at welded joints accounted for over 80% and became the most dangerous failure mode for welded structures [3]. In the past twenty years, the super long life fatigue properties of base materials have been studied extensively. However, the fatigue behaviors of welded joints were rarely studied, especially in very high cycle fatigue (VHCF) regime. Therefore, the study on VHCF behaviors of welded joints is of significant importance for the safe operation of welded structures.

The VHCF behaviors of heat affected zone (HAZ) and fusion zone (FZ) were investigated with ultrasonic fatigue test system by Cremer et al. [4] and the influences of microscopic and macroscopic notch effects on the VHCF behavior were analysed for an Al alloy systematically. Yin et al. [5] found that the fatigue limit of welded joints could not be observed in the VHCF region and the fatigue strength of welded joints could be enhanced apparently by ultrasonic peening treatment. Zhu et al. [6] investigated the VHCF behavior of a low strength welded joint at moderated temperature and found that the higher potential for interior crack nucleation at higher temperature was ascribed to matrix softening, surface oxidation and surface compressive residual stress. To date, most studies on welded joints focused attention on the experimental fatigue strength and failure mechanism in the VHCF, while the evolution of fatigue damage and life prediction model of different subzones were not discussed due to the difficulty of stress or strain detection in ultrasonic fatigue.

In this work, a specially designed specimen was fatigued in VHCF regime to investigate the fatigue performances of HAZ and FZ for welded joints. The VHCF failure mechanism was addressed with the help of scanning electronic microscopy (SEM) and the fatigue crack propagation life was estimated by analysing the relationship between crack size and natural frequency using finite element method (FEM). Finally, a new damage model based on the variation of frequency during fatigue was proposed for welded joint in the VHCF regime.

2. Material and experimental method

The material used in this study was a widely used low-alloy steel, Q345, with yield strength of 420 MPa. The chemical composition and mechanical properties are presented in Tables 1 and 2, respectively. The microstructure of base material (BM) is mainly composed of ferrite as shown in Fig. 1a. In comparison with BM,

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Table 1
Chemical composition of the base metal and solder (wt.%).

Material	C	Si	Mn	S	Alu	P	Mo	Fe
Q345q (base metal)	0.15	0.38	1.36	0.00003	–	0.00012	0.00002	Rest
E45 (solder)	–	0861	2.236	–	0.648	–	1.569	Rest

Table 2
Mechanical properties of Q345 steel in this work.

E (GPa)	σ_y (MPa)	UTS (MPa)	ρ (g cm^{-3})	A (%)	HV30
201	420	570	7.85	13	136

a mixed microstructure of ferrite and pearlite caused by welding process at high temperature (Ac3–Ac1) could be observed in HAZ (Fig. 1b). For FZ (Fig. 1c), widmanstatten microstructure mixed with acicular ferrite and pearlite is formed by air cooling after austenitization. Fig. 1d shows the hardness of weld joint. It is shown that FZ and HAZ have a higher hardness than that of BM.

The welded joint specimens were machined from butt-welding plates with a thickness of 10 mm. Fig. 2a shows the dimension of fatigue specimens. The radius of rounded roof for the specimen was specially designed to 2 mm and other dimensions were determined by the method introduced in literature [7]. The welding area located in the middle of the rounded roof for FZ specimen (Fig. 2b) and a distance of 4 mm was designed for HAZ specimen (Fig. 2c). In ultrasonic fatigue test, the maximum stress always located in the middle of specimen. The FEM results showed that specially designed specimen was better to restrict the high stress at the root of arc during fatigue, as shown in Fig. 2d. Ultrasonic fatigue tests of BM were also carried out for the comparison of fatigue strength.

Fatigue tests were performed on the USF-2000 ultrasonic fatigue test system up to a limit of 10^9 cycles under the condition of stress ratio $R = -1$ and at room temperature. The compressed air was used to cool the specimens during fatigue. The variation of resonance frequency of each specimen was measured by the computer control system.

3. Results and discussion

3.1. S–N curves

Fig. 3 shows the S–N curves for the three groups of specimens obtained from ultrasonic tests. The specimens running out over 10^9 cycles are indicated by arrows. It is seen that the fatigue strength of HAZ and FZ was much lower than that of BM, with a percentage of 51.4% and 42.8% at 10^9 cycles, respectively. The weakness of the VHCF fatigue strength of welded joints was also obtained in literature [8] for EH36 welded joints. Due to the cycling of local high temperature during welding process, unmatched mechanical properties and discontinuous microstructures throughout the welded joint were induced, which could induced the crack initiation. The S–N curves of BM and HAZ decrease continuously to gigacycle range (10^9 cycles) without apparent fatigue limit. For FZ specimen, a duplex shape of the S–N curve can be observed at a transition of 5.6×10^6 cycles and a nearly horizontal platform maintains at a stress of about 145 MPa, which could be regarded as the traditional fatigue limit. According to [9] and [10], the platform of S–N curve for high strength steel SUJ2 was related to the transition from surface to internal crack initiation [11]. In this test, no platform of BM and HAZ was observed possibly because of the absence of internal fatigue crack initiation. However, the welding process caused many defects such as micro cracks, pores and inclusions in FZ, which could result in the internal crack

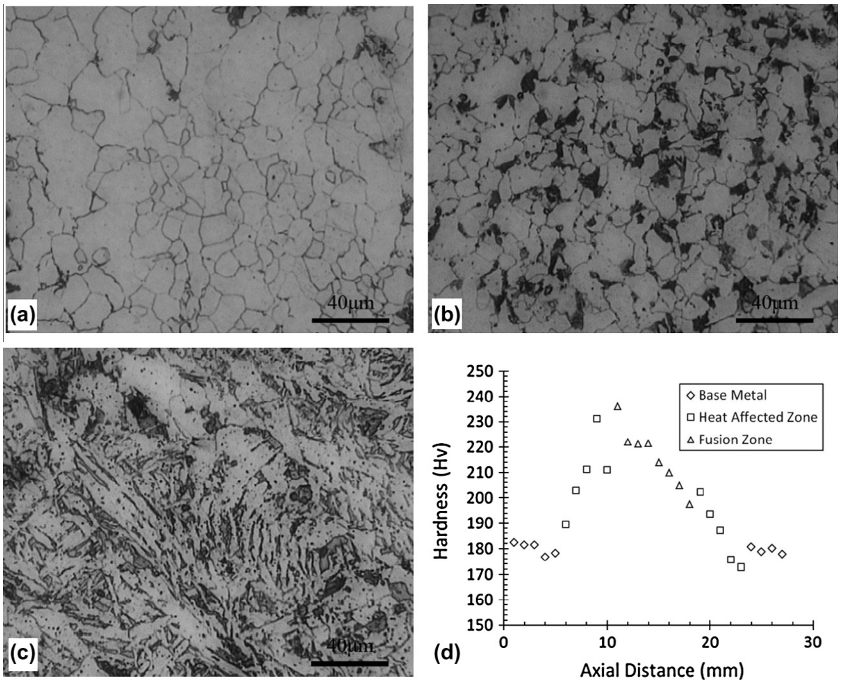

Fig. 1. Metallurgical structure of welded joint in this work; (a) base metal (ferrite); (b) heat affected zone (ferrite and pearlite); (c) fusion zone (widmanstatten structure); and (d) hardness profiles of different subzones.