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Enhancement of the fatigue strength of underwater wet welds by grinding and ultrasonic impact treatment

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ABSTRACT

Grinding + underwater ultrasonic impact treatment (UUIT) is proposed to improve the fatigue property of underwater wet welded joints. Using single grinding or UUIT technique cannot improve the fatigue life significantly while the combination of the two can obtain great enhancement. The microstructures in the weld metal contain proeutectoid ferrite, side-plate ferrite and acicular ferrite and the microstructure in coarse grain heat affected zone (CGHAZ) is dominated by martensite. Compressive residual stress decreases the effective stress intensity factor range and extends the fatigue life. The transverse residual stresses on the surface of as-welded joint are compressive due to the fast cooling effect of water and it is less in weld metal (WM) than in CGHAZ, which results in the initiation of fatigue crack at WM.

1. Introduction

Underwater wet shielded metal-arc welding is widely applied in basic repairs of offshore structures because of its versatility and low cost compared with other repair techniques. Rowe and Liu (2001) revealed that the main problems of this technique were related with the presence of water around the electric arc, which caused higher cooling rate, arc instability, and large amounts of oxygen and hydrogen in the arc atmosphere.

For underwater wet welding, most previous experiments have focused on the common mechanical properties or the metallurgical aspects of the welds obtained with different compositions of the electrode rod, coating, or waterproof materials. Pessoa et al. (2006) found that porosity reduced along the multi-pass underwater wet welds and samples extracted from the end of the welds showed higher strength and ductility. Jia et al. (2013) studied the spectroscopic analysis of the arc plasma of flux-cored arc welding in air and under water. They found that the two sets of spectrum signals were largely similar and a unique peak at 656.2793 nm existed in the underwater spectrum suggesting that H atoms became involved. Santos et al. (2012) developed an oxyrutile electrode for wet welding combining the good operability of rutile electrodes and the low diffusible hydrogen content. The mechanical properties of welds obtained at shallow water exceeded the requirements for AWS D3.6 Class A Weld. Perez et al. (2003) added nickel to oxide electrode covering and showed that 2% (wt.) nickel could obtain the optimal Charpy impact values. In addition, Rowe et al. (2002) studied the influence of adding ferro-alloy additions on the quality of wet welds.

However, it should be emphasized that published research on the fatigue behaviour of underwater wet welds is still rare. Moreover, there are almost no reports on the application of underwater ultrasonic impact treatment (UUIT) to strengthen the fatigue performance of underwater wet welds. Therefore, the current research on this field is particularly significant.

Haagensen and Maddox (2006) showed that burr grinding, tungsten inert gas (TIG) dressing, hammer peening, and needle peening were the most commonly applied post weld treatments for improvement of fatigue behaviour of welded joints. Yildirim and Marquis (2012) showed that ultrasonic impact treatment (UIT) is considered an ideal method because of its easy operation, high efficiency and low cost. TIG dressing cannot be directly applied under water. So in this study burr grinding and UUIT were utilized to improve the fatigue behaviour. The microstructure, residual stress and fracture morphology were also discussed.

2. Experimental procedure

The base metal was DH36 steel plate with a thickness of 12.7 mm. The filler material was an E7014 underwater electrode

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Table 1
Chemical compositions of materials used in this study, wt.%.

Material	C	Si	Mn	Al	Nb	V	Ti	O	CE[a]
Base metal	0.13	0.18	1.4	0.02	0.02	0.05	0.012	–	0.373
Filler material	0.073	0.31	0.46	0.006	–	–	0.012	0.042	–

[a] $CE = C + M_n/6 + (C_r + M_o + V)/5 + (N_i + C_u)/15$.

Table 2
Mechanical properties of materials used in this study.

Material	Yield strength (MPa)	Tensile strength (MPa)	Elongation rate (%)
Base metal	375	510	30
Filler material	476	523	8.0

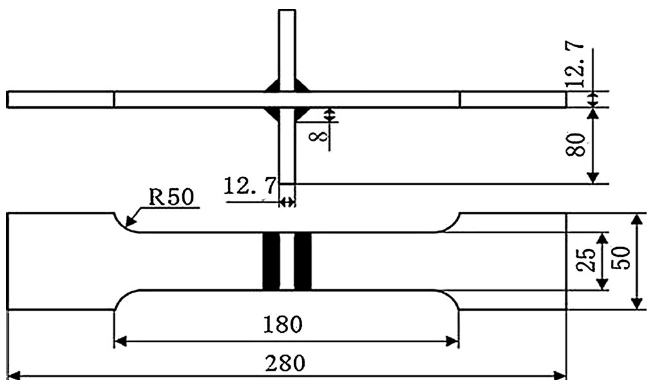

Fig. 1. Geometric characteristics of specimen (all dimensions in mm).

with a diameter of 3.2 mm and a waterproofing of wax. The chemical composition and mechanical properties are listed in Tables 1 and 2, respectively.

The underwater joints were welded in the 3G down position (AWS D3.6 M:2010) in a tank. The water temperature and water depth were 20 °C and 2 m, respectively. The welding parameters were as follows: arc voltage of 24–26 V, welding current of 153 A and welding speed of 300 mm/min. Each fillet weld included three passes. 45 non-load-carrying transverse cruciform specimens (Fig. 1) were prepared. Specimens were divided into four groups: as-welded, burr grinding, UUIT and burr grinding + UUIT. Burr grinding was carried out according to the Recommendations on Post Weld Improvement of Steel and Aluminium Structures of IIW described by Haagensen and Maddox (2006). As shown in Fig. 2a, the UUIT system consists of four parts: an ultrasonic (20 kHz) frequency generator, an ultrasonic impact gun, ultrasonic horn and an air compressor. The radius of the needle tip is 2 mm. The UUIT process was conducted in a water container, as shown in Fig. 2b. Air was continually compressed into the gun to protect it from the water. The treatment parameters were as follows: a frequency of 20 kHz, vibration amplitude of 25 μm, treating speed of about 1.0–1.5 m/min, and treatment coverage of 200% (treatment coverage is defined as the ratio of the area covered by the shot impacts to the complete surface of the treated sample).

Fatigue tests were conducted under a constant amplitude tensile load with a stress ratio (R) of 0.1 at room temperature. A 300 kN HF fatigue testing machine of CIMACH GPS 300 was utilized. An OLYMPUS GX51 optical microscope (OM) and a scanning electron microscopy (SEM) of Hatchi S-4800 were used to observe the microstructure of the joint after being polished and etched by nital solution (4% HNO_3, 96% C_2H_5OH by volume). The standard $\sin 2\psi$ X-ray diffraction technique was used to measure the residual stress. The material removal in the depth direction was achieved by electrolytic polishing. The microhardness values were measured using a Microhardness Tester MHV2000. Then, cross-sectional morphologies and fracture surfaces of the joints were observed by OM and SEM.

3. Results

3.1. Microstructure

Fig. 3 depicts typical OM and SEM images showing the microstructures of the underwater wet welded joint. The microstructure of the base metal (BM) consists of a banded structure with fine elongated ferrite (F) and pearlite (P) grains (Fig. 3a). As shown in Fig. 3c and e, the columnar microstructures in the weld metal (WM) are characterized by proeutectoid ferrite (PF), side-plate ferrite (SPF) and a small amount of acicular ferrite (AF). The PF can nucleate at the boundaries or at the inner microdefects in the austenite grains. In the SPF, the proeutectoid phase separates inside the grains along certain crystallographic planes. SPF sharply decreases the toughness of the weld metal.

The microstructures of the coarse-grained heat affected zone (CGHAZ) (Fig. 3d and f) include lath martensite (M) containing differently oriented packets with several fine parallel laths and some retained austenite. Since CGHAZ could not be totally protected by the bubbles, the rapid cooling effect of water leads to the generation of quenching microstructure. In fact, Johnson (1997) reported that the cooling time $t_{8/5}$ (from 800 °C to 500 °C) at the point 1 mm distant from the fusion line on the plate surface did not exceed 2 s. The lath martensite of CGHAZ has a very high hardness, which makes it easy to generate hydrogen-induced cracks due to the large amounts of hydrogen in the joint.

3.2. Fatigue behaviour

The fatigue testing data were analysed according to the IIW statistical method described by Hobbacher (2008). The *S*–*N* curves were fitted based on the following formulae:

$$C_m = N(\Delta\sigma)^m \quad (1)$$

where C_m represents 50% survival probability calculated from the mean on the basis of two-sided tolerance limits at the 75% level; N is the number of cycles to failure; $\Delta\sigma$ is the nominal stress range at the weld toe; m is the characteristic value. The statistical results are listed in Table 3. The characteristic values m of the four *S*–*N* curves range from 5.51 to 7.44, which are all larger than the value ($m = 3$) suggested in the fatigue design criteria of the IIW.

Fig. 4 shows the *S*–*N* curves of the four groups of specimens. Table 4 shows the fatigue strength data corresponding to 2×10^6 cycles. It is 135 MPa for the as-welded specimens, which is increased by burr grinding, UUIT and burr grinding + UUIT by

Table 3
Statistical results of fatigue test data.

Status	Stress ratio R	m	C_m	Fitted equation
As-welded	0.1	5.51	1.259×10^{18}	$1.259 \times 10^{18} = N(\Delta\sigma)^{5.51}$
Burr grinding	0.1	6.26	1.381×10^{20}	$1.381 \times 10^{20} = N(\Delta\sigma)^{6.26}$
UUIT	0.1	7.44	1.389×10^{23}	$1.389 \times 10^{23} = N(\Delta\sigma)^{7.44}$
Grinding + UUIT	0.1	6.86	2.375×10^{22}	$2.375 \times 10^{22} = N(\Delta\sigma)^{6.86}$