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Evaluation of inhomogeneity in tensile strength and fracture toughness of underwater wet friction taper plug welded joints for low-alloy pipeline steels

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ABSTRACT

The microstructural characteristics of underwater wet friction taper plug welded joints for API X52 pipeline steel were investigated and tensile strength and facture toughness of the welded joints were experimentally evaluated. The microstructure of welded joints is considerably inhomogeneous. The tensile strength of welded joints shows heterogeneity in thickness direction. All of the tensile specimens taken from upper side of welded joints fracture at base material, while those taken from the bottom are broken at bonding interface or base material. The fracture toughness of welded joints deteriorates seriously, as compared with base material. The welded joints with notches in weld center have higher fracture toughness than those in bonding zone and the axial force has few influences on fracture toughness of welded joints. The bonding zone between plug and base plate should play a role as fissure defect for the whole welded joint, considering that it is tens of microns and much softer than its vicinity. In addition, the coarse grain, quenched martensite and Widmanstätten ferrite in weld region should also be responsible for the reduction of fracture toughness.

1. Introduction

Friction taper plug welding (FTPW) technology developed from traditional rotating friction welding is a new solid-state welding process. The fundamental process is that the plug becomes thermal-plastic due to the frictional heat generated by mutual friction between plug with high rotational speed and the hole bottom under axial force, and fills the hole eventually. Friction taper plug welding (FTPW) takes the advantages of much lower heat input, high efficiency, excellent weld quality and smaller distortion as compared with underwater arc welding technology [1–3]. In particular, FTPW is insensitive to water depth. Thus, FTPW is considered as the most promising underwater wet repair and join technology in deep water and has good prospects in the repair of marine structures and underwater oil and gas pipeline [4–7].

Many researches have been made on FTPW and they are mainly focused on equipment, welding process, microstructural evolution, effects of weld geometry on FTP welded joints and general mechanical properties of welded joints. Zhou et al. developed a friction stitch welding equipment to satisfy tubular structures repairing [8]. Lessa observed the variation of parameters and gave attention to the microstructure and quality of repair [9]. Unfried described microstructural evolution of friction taper plug welded joints of C-Mn steels [10]. Yeh et al. found and evaluated the discontinuities within the repairs [11]. Chludzinski et al. analyzed the fracture toughness characteristics of friction hydro-pillar process welded joints in C-Mn steels and concluded that the manganese sulfide inclusions should be responsible for the decrease in toughness [12]. We also have carried out many experiments confirming the feasibility of FTPW and investigating welding process, microstructural characteristics and mechanical properties of weld metal [13–17]. For low-alloy pipeline steel, it is found that the microstructure of FTP welds is significantly inhomogeneous and FTP welds are obviously hardened. Besides, FTPW process brings a decrease in plasticity and toughness. However, researches about the deterioration of plasticity and toughness for underwater wet friction taper plug welded joints are scarcely reported. There is no comprehensive evaluation on strength and toughness for the whole FTP welded joints and the effects of microstructure on fracture toughness of welded joints for pipeline steel have not been discussed. On the other hand, high strength and toughness are demanded for pipeline steels due to higher pressure applied on pipeline steel in order to realize efficient transportation of oil and gas and the harsh working condition underwater. Therefore, it is essential to evaluate the

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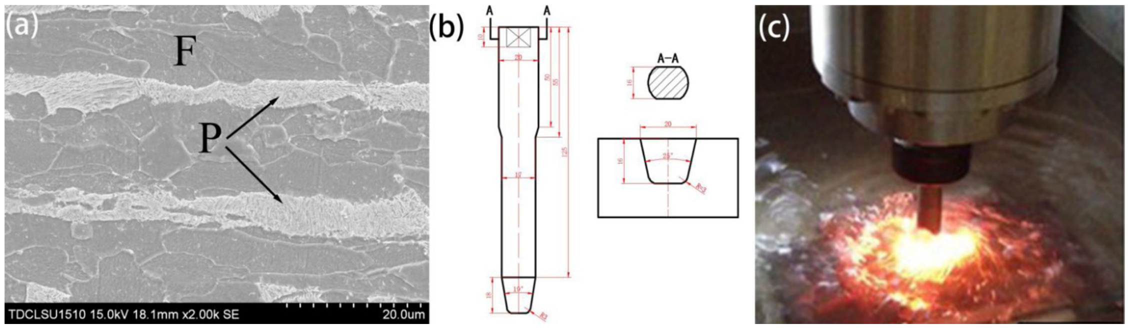

Fig. 1. (a) Microstructure of base material, (b) Geometries of plug and hole, (c) Underwater wet condition.

tensile strength and fracture toughness of underwater wet friction taper plug welded joints for pipeline steel.

The present study aims to evaluate the tensile strength and fracture toughness of underwater wet friction taper welded joints for pipeline steel and analyze the effects of microstructural characteristic on them. Microstructure of welded joints was observed in detail and tensile tests taken from different thickness of welded joints were performed. Crack tip opening displacement (CTOD) is an index of elastic-plastic fracture toughness, so that three point bend tests were operated to calculate CTOD values to evaluate the facture toughness of underwater wet friction taper plug welded joints and base material in this study. Furthermore, the effects of welding parameters on tensile strength and fracture toughness of underwater wet friction taper plug welded joints for pipeline steel were also explored. Finally, pre-crack propagation paths were analyzed and the relationships between microstructure and tensile strength and the fracture toughness were discussed.

2. Experimental procedures

The base plates with the size of 200 × 25 × 28 mm and plugs were cut from X52 grade pipeline steel. The microstructure of base material is polygonal ferrite (F) with banded pearlite (P), as shown in Fig. 1 (a).The underwater wet friction taper plug welding experiments were performed with optimized welding parameters on a machine designed and developed by Tianjin University in 2012. The optimized welding parameters are listed in Table 1 [14].The fixed geometries of hole and plug are shown in Fig. 1(b), according to our previous research work. The base plate and plug were completely immersed in water to simulate an underwater wet condition, as shown in Fig. 1(c).

After the welding process, the metallographic specimens obtained by being cut along center line of plug were water milled, mechanically polished and etched with 3% nital solution. The microstructure of welded joints was observed by optical microscopy and Vickers micro-hardness tests were conducted on metallographic specimens at 2 mm, 7 mm, 12 mm and 17 mm below top surface respectively with 1 Kg load held for 15 s. Tensile specimens were taken from both upper and lower part of the joints, as shown in Fig. 2(a). Tensile tests were performed on universal testing machine with 5 mm/min loading speed. The sampling positions and the dimensions of CTOD specimens determined by BS 7448 standard are shown in Fig. 2(b). The straight notch was opened at weld center (WC) / bonding zone (BZ) of welded joints or the middle of base material CTOD specimen. A fatigue crack of restricted shape and size was developed from the tip of the machined notch on a GSP10 high frequency fatigue testing machine at room temperature before the three point bend test. The maximum fatigue precracking force *F*max is determined by the following formula.

$$F_{max} = \frac{B(W-a)^2(\sigma_{YS}+\sigma_{TS})}{4S}$$

B specimen thickness
W specimen width
a an assumed crack length
σ_{YS} yield strength
σ_{TS} tensile strength
S the span between outer loading points in three point bend test

In addition, the average load equals to 0.55*F*max, and the alternating load equals to 0.45*F*max. The minimum fatigue crack extension shall be the larger of 1.3 mm or 2.5% of the specimen width *W*. Three point bend tests were performed on universal testing machine at room temperature with a 1.0 mm/min loading rate. The force-crack tip open displacement ($F \sim V$) curves were recorded during the tests and the specimens were pressed off after three point bend tests to measure the original crack lengths. SEM was performed on a TDCLSU1510 scanning electronic microscope to investigate the fracture morphologies of tensile specimens and CTOD specimens. Post-test metallographic specimens were prepared to observe crack propagation behavior by TDCLSU1510 scanning electronic microscope, as shown in Fig. 2(c).

3. Results and discussions

3.1. Microstructural inhomogeneity

It is observed from Fig. 3(a) that defect-free welded joints are obtained. The bonding interface which keeps the original shape

Table 1
Optimized welding parameters.

Rotational speed/rpm	Welding force/kN	Forging force/kN	Forging time/s	Burn-off/mm
6500	40	45	5	14
7000	30	35	5	14
7000	35	40	5	14
7000	40	45	5	14
7000	45	50	5	14
7500	35	40	5	14
7500	40	45	5	14
7500	45	50	5	14