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Fracture toughness of the materials in welded joint of X80 pipeline steel

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ABSTRACT

The microstructures, mechanical properties and fracture toughness of the materials in different locations of the welded joint of the X80 pipeline steel were studied at room temperature. Elastic–plastic fracture toughness testing of crack tip opening displacement (CTOD) and *J*-integral of the welding materials and base material were conducted. A new non-contact double-clip gauge measuring system was developed and used in the fracture toughness tests. It was observed the fusion zone (FZ) was the fracture risk zone of the X80 steel weldment; and the occurrence of hard-brittle martensite–austenite (M–A) constituents was a significant because of welding hardening and embrittlement.

1. Introduction

Pipeline is a convenient, economic and safe way of transporting petroleum and natural gas with high pressure for long distances. In recent years, the demand for petroleum and natural gas is gradually on the increase, and the capacity of oil–gas pipeline transportation has been developing greatly. The X80 steel pipelines, with high strength, toughness, weldability and corrosion resistance, have been used in the project of natural gas transmission from West to East China [1]. The X80 steel is a kind of high strength low alloy (HSLA) steel and the technique of thermal–mechanical control process (TMCP) has been widely applied to manufacture the X80 steel pipelines [2]. The welded joint of a long-distance transport pipeline, which has heterogeneous textures and characteristics, welding defects and so on, tends to be a weak link for rupture [3]. Lee et al. [4] reported that the local brittle zone (LBZ) of the heat affected zone (HAZ) of the welded joint of TMCP steels appeared, attributed mainly to the significant increase in the amount of martensite. Rak and Treiber [5] reported that due to mismatch of weld joints fabricated in HSLA steels, fracture deviation from the coarse-grained heat affected zone (CGHAZ) into weld or base metal occurred. Lambert-Perlade et al. [6] reported both the martensite–austenite (M–A) constituent and the coarse upper bainite microstructure in simulated welding HAZ microstructures of a HSLA steel have a deleterious effect on the toughness properties. Moeinifar et al. [7,8] found that the morphology of M–A constituents has an influence on the hardness values and fracture toughness of the HAZ in the X80 pipeline steel. Moreover, oil–gas pipelines are often used in harsh environments such as freezing areas and corrosive soils [9,10], so the investigation of the fracture toughness of the welded joints of X80 steel pipeline is of significant importance.

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Nomenclature

a_0	average initial crack length
a_f	average final crack length
a_m	average machined notch length
B	thickness of the single edge notched bending specimen
B_N	net thickness of the single edge notched bending specimen
E	elastic modulus
EPFM	elastic–plastic fracture mechanics
F	applied force
$g_1\left(\frac{a_0}{W}\right)$	shape factor of the single edge notched bending specimen
J	J integral value
$J_{0.2BL}$	critical J integral, acquired by the 0.2mm offset blunting line
q	displacement of the applied force
R_m	ultimate strength at the temperature of the fracture test
$R_{p0.2}$	0.2% offset yield strength at the temperature of the fracture test
S	span of the single edge notched bending specimen
U_p	plastic strain energy
V, V_1, V_2	crack opening displacements (COD)
V_p	plastic component of the COD
W	width of the single edge notched bending specimen
Z, Z_1, Z_2	distance of the clip gauge location above the surface of the specimen
α, β, γ	fitting coefficient of the blunting line equation
δ	crack tip opening displacement (CTOD)
$\delta_{0.2BL}$	critical CTOD, acquired by the 0.2mm offset blunting line
Δa	average crack propagation length
Δa_k	average crack propagation length during the loading/unloading at the k time
ν	Poisson's ratio

Although the fracture toughness of X80 pipeline steel has been studied comprehensively using the Charpy V notch (CVN) test and the drop-weight tear test (DWTT) [7,8,11–14], these impact tests are suited to evaluate fracture toughness of HSLA steel pipelines under dynamic loading conditions. For structural integrity assessments of pipelines welded joints, it is also important to carry out fracture toughness tests of HSLA steel under service loading, i.e. static loading conditions. Elastic plastic fracture mechanics (EPFM) toughness test method [15–17], particularly the one using single edge notched bending (SENB) specimens, is a practical and feasible way of measuring the fracture toughness of ductile metal. Wells [18] proposed the crack tip opening displacement (CTOD) to characterize the resistance to cracking at a crack tip of a material. Rice [19] proposed the J integral as a parameter to represent the intensity of the stress and strain field at a crack tip. These two parameters were used to describe the fracture toughness in EPFM method. Zerbst et al. [14] recommended the EPFM method to evaluate the fracture toughness of thin-wall structures such as pipelines and pressure vessels, according to engineering applications.

In this study, the different locations of the welded joint of the X80 steel pipeline are investigated covering the entire range of weld seam. The hardness distribution test, the metallographic observation, the uniaxial tensile test, and the EPFM fracture toughness test at room temperature are carried out. The metallurgical structures, the basic mechanical properties, and the fracture toughness values of the X80 steel pipeline at different locations of welded joint are obtained. The variation of the fracture toughness values of the X80 steel weldment is discussed on the basis of the microstructures.

2. Experimental procedures

2.1. Material

The welded joint for test was taken from the longitudinally submerged arc welding (LSAW) pipeline of X80 steel at the job site of the natural gas transmission from West to East China as shown in Fig. 1. The external diameter of the pipeline is 1219 mm, and the thickness is 22 mm. The submerged arc welding process was conducted with an asymmetric double-V groove, four internal solder wires and five outer solder wires. During the welding process, the welding speed used was 1.75 m/min for both inside and outside welds; and the heat input rates were 43.4 kJ/cm, and 51.5 kJ/cm for inside and