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Interaction of welding residual stresses and warm pre-stressing on brittle fracture of a pipe containing an internal semi-elliptical crack

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ABSTRACT

Residual stresses (RS) due to welding process, may change the load bearing capacity of cracked components. These stresses can also affect the benefit of warm pre-stressing (WPS) cycles which are used for improving structure behaviour. RS are obtained from a two-passes welding simulation of a pipe and verified by experiments. A semi-elliptical internal crack at the weld line is considered. Redistribution of RS field after introducing the crack shows a significant tensile RS are remained at the crack tip. Two common WPS cycles, load-cool-fracture (LCF) and load–unload-cool-fracture (LUCF), are applied using the model at room and low temperature subjected to axial loading. Using local approach to fracture shows that welding RS dramatically raise the fracture probability. LCF has more influence on reducing the fracture probability in comparison with LUCF. The interaction of welding RS and WPS cycles still improves the fracture properties, however, welding RS cause to decrease the benefit of WPS. Comparing RS distributions on crack-tip shows that applying WPS cause to release a significant amount of welding RS and therefore, WPS can be very useful for welded structures. The near crack-tip opening stresses at a same fracture load are further studied for all cases.

1. Introduction

It is widely accepted that the presence of the welding residual stresses (RS) can have a significant effect on the subsequent failure characteristics of engineering components and structures [1]. They can be added to service stresses as the secondary stresses and change the failure characteristics [2]. However, the role of RS on failure and integrity assessment has received relatively little attention in comparison with other effects of welding, which due largely to historical difficulties associated with the measurement and prediction of RS [3]. Reviews of the treatment of RS in the defect assessment of welded structures have been discussed by Budden and Sharples [4], and Dong and Brust [5].

Using FEM to simulate welding RS has received much attention lately. Dar et al. [6] and Yi et al. [7] conducted a finite element (FE) analysis of the welding residual stresses and distortion in cylinder-shaped weldments. The element birth technique was used in the filler metal deposition in both studies. The simulations were validated against measurements of residual stress determination. Yi et al. also studied the effects of heat input energy and deposition sequence on welding residual stress and distortion [7]. Besides, Moshayedi and Sattari-Far investigated the effect of welding parameters on welding pool

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and welding RS [8,9]. They showed that however using optimum welding parameters cause to decrease the RS level in the specimens, but there would be still a considerable amount of RS with using the best welding parameters. Recently, Testa et al. discussed the importance of incorporating the stress–strain state resulting from thermomechanical process on integrity assessment of a welded structure [10]. Simulating a multi-pass welding, they showed that the RS distribution can differ from that provided in the design codes.

Among the factors affecting the lower bound brittle fracture, one counts the effect of prior loading of a cracked body at a temperature above the ductile–brittle transition on the effective fracture toughness measured at a lower temperature in the brittle regime [11]. This technique is called warm pre-stressing (WPS) and can improve the resistance of a structure to brittle fracture if the crack receives tensile preload. Besides crack blunting and increasing yield stress due to work hardening, one of the main factor causes WPS to improve fracture toughness is introducing local compressive RS at the crack tip [12]. Any possible combination of temperature–load–unload–reload can be realized that will result in variation of the effective fracture toughness with respect to as-received material. Moinereau et al. applied different WPS cycles on A508 and A533B steel CT specimens [13]. Their experiments show that load-cool-fracture (LCF) cycle has the most influence on CT specimens. One of the other WPS cycles which is well-known and common for pressure vessels and pipes is load-unload-cool-fracture (LUCF). In this work these two kind of preloads are considered as WPS cycles. Lately, Ilchuk et. al. studied the effect of LUCF cycle on cleavage fracture of Eurofer97 sub-sized CT specimens [14]. They reported that a great increase has been occurred in measured fracture toughness due to applying WPS. On the other side, Moshayedi and Sattari-Far recently investigated the effect of welding RS on fracture probability of welded pipe [15]. They showed that failure probability would decrease dramatically in the presence of welding RS. Therefore, it can be concluded that in the presence of cracks the benefit of WPS depends on the combination of crack geometry, loading conditions and initial RS. If there RS, the stress field due to the applied WPS will interact with the initial RS.

The local approach based on Beremin model is a statistical model for cleavage fracture considering the micromechanisms of failure at a local scale, and incorporates a weakest link concept [16]. The original model and its extensions are the most widely applied approaches to predict cleavage fracture [12]. A prevalent local stress based model suggests using parameters calibrated based on material response at the specified test temperature regardless of the crack/loading configuration [16]. This model was used to predict the influence of WPS on brittle fracture in standard fracture mechanics specimens [17]. This study uses the proposed local approach model for predicting the effect of welding RS, WPS cycles and combination of them on brittle fracture properties of a pipe contains an internal partial surface crack.

2. Experimental tests

Two 130 mm diameter A533B ferritic steel pipes with a wall thickness of 6.25 mm and a length of 131 mm were used for this study. A two-passes GTAW process with the welding parameters presented in Table 1 was applied. Weld joint specifications are described in Fig. 1. Fig. 2 shows the welded pipes on the rotating fixture. Three internal brackets were used to minimise distortion and maximising RS.

The Hole Drilling Strain-Gauge (HDSG) method was used for measuring RS. Ref. [18] discusses in details the application of this method and calculating RS. Fig. 3 shows the location of the strain-gauges. The third gauge was located on the opposite side of the weld, due to the limitations in the minimum distance between gauges, according to ASTM E837-01 [19]. Strain gauges of the "A" rosette type were mounted on the pipe at the selected points to measure the released strains after drilling in the centre point of the gauges by a very high-speed drill. Surface preparation technique was done according to ASTM E837-01 standard [19]. Incremental hole drilling technique and recommended data analysis method in this standard were used. The drilled hole diameter was 1.84 mm and as deep as 2 mm. Fig. 4 shows HDSG measuring set up used for obtaining welding RS. After measuring the released strains by a strain indicator, the stresses in the axial and hoop directions were calculated according to the following equations, based on the ASTM E837-01 standard [19]:

$$\begin{cases} \sigma_{max}, \sigma_{min} = P \pm \sqrt{Q^2 + T^2} \\ P = -E \times (\sum \bar{a} \cdot p)/(\sum \bar{a}^2)/1 + \upsilon \\ Q = -E \times (\sum \bar{b} \cdot q)/(\sum \bar{b}^2) \\ T = -E \times (\sum \bar{b} \cdot t)/(\sum \bar{b}^2) \end{cases} \tag{1}$$

where E is elastic modulus and υ is Poisson's ratio. $\bar{a}$ and $\bar{b}$ are dimensionless coefficients which vary with hole depth and are indicated in ASTM E837-01 standard for different strain gauge types and hole diameters [19]. p, q and t are combination strains and can be defined from measured strains ε_1, ε_2, ε_3 in each increment as follows:

Table 1
Welding parameters.

Pass no.	Current (Amp)	Voltage (Volt)	Speed (mm/min)	Inert gas flow rate (lit/min)
1	117	10.6	74.0	7
2	117	10.5	66.7	7