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Characterization of crack tip stresses in plane-strain fracture specimens having weld center crack

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ABSTRACT

Fracture toughness of metals depends strongly on the state of stress near the crack tip. The existing standards (like R-6, SINTAP) are being modified to account for the influence of stress triaxiality in the flaw assessment procedures. These modifications are based on the ability of so-called 'constraint parameters' to describe near tip stresses. Crack tip stresses in homogeneous fracture specimens are successfully described in terms of two parameters like J–Q or J–T. For fracture specimens having a weld center crack, strength mismatch ratio between base and weld material and weld width are the additional variables, along with the magnitude of applied loading, type of loading, and geometry of specimen that affect the crack tip stresses. In this work, a novel three-parameter scheme was proposed to estimate the crack tip opening stress accounting for the above-mentioned variables. The first and second parameters represent the crack tip opening stress in a homogeneous fracture specimen under small-scale yielding and are well known. The third parameter accounts for the effect of constraint developed due to weld strength mismatch. It comprises of weld strength mismatch ratio (M, i.e. ratio of yield strength of weld material to that of base material), and a plastic interaction factor (I_p) that scales the size of the plastic zone with the width of the weld material. The plastic interaction factor represents the degree of influence of weld strength mismatch on crack tip constraint for a given mismatch ratio. The proposed scheme was validated with detailed FE analysis using the Modified Boundary Layer formulation.

1. Introduction

Fabrication of many engineering structures such as nuclear pressure vessel, piping, boilers, marine structures, etc. involves invariably the joining of metal components whereby welding is a necessity. In general, cracks get developed in the weldments either during the fabrication process and/or in the service life of the structure. A realistic fracture assessment of these welds is an important aspect of integrity assessment of these load bearing structures. Conventional flaw assessment procedures require estimation of the crack driving force and a measure of fracture toughness. The existing structural integrity assessment methods (Kumar et al., 1981; R6, 1998; Schwalbe et al., 1997) for pressure retaining components were developed mainly for nominally homogeneous materials. ASTM E1921-13 (2013) covers the determination of a reference temperature, T_o, which characterizes the fracture toughness of ferritic steels and weld metals, after stress-relief annealing, that have 10% or less weld strength mismatch ratio. The statistical effects of constraint arising due to specimen size and geometry on K_{Jc} in the transition range are treated using weakest-link theory applied to a three-parameter Weibull distribution of fracture toughness values. These conventional procedures need to be modified to account for the influence of weld strength mismatch. Many investigators in past (Kocak et al., 1988; Kirk and Dodd's, 1993; Michiba et al., 1994) found that J–R curves of welded fracture specimens are affected by the strength mismatch between the yield strength of base and weld material as well as by the weld geometry. These studies indicate that weld strength mismatch, weld width and crack location have significant effect on crack tip stresses and, hence, on the fracture toughness of weld joint. To transfer the fracture properties from laboratory specimen to an actual component a systematic investigation of crack tip stresses accounting for the weld mismatch effects is required. Several investigations have been performed in past to quantify the weld mismatch effects on crack tip stresses (Kim and Schwalbe, 2004; Ranestad et al., 1997). The problem of a crack lying at the interface of two materials has been extensively examined (Fu and Shi, 1996; Ganti et al., 1997; Hyungyil and Kim, 2001; Kim et al., 1997; Ruggieri et al., 1993; Zhang et al., 1996, 1997). For weld center cracks, Burstow et al. (1998a,b) have accounted for the effect of material mismatch on near tip stress by modifying T-stress, for an elastic perfectly plastic material. T-stress was modified by a constraint parameter that is a function of strength mismatch ratio, M and normalized

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load parameter, $J/h\sigma_0$. Although the proposed scheme can describe the level of mismatch induced constraint at a particular point ahead of crack, that is, at $r/J/\sigma_o = 2$, it cannot account for its radial variation along the crack plane. Ductile fracture studies performed by Ritchie and Thompson (1985) and Ritchie et al. (1973) suggest that the distribution of near tip stresses over the microstructurally relevant zone (typically of the order of $1 \leqslant r/J/\sigma_o \leqslant 5$) control the fracture process. Moreover, the normalized load parameter proposed by Burstow et al. (1998a) is valid only for non-zero T-stress. The effect of T-stress on plastic zone size are, however, well recognized.

With the tremendous enhancement of computational power, a detailed and physically based description of damage phenomena is also used, now a days, to numerically simulate the materials' constitutive response. Within this general framework, damage and rupture is represented on a surface such as 'cohesive zone model' (Cornec et al., 2003; Faizan and Banerjee, 2013; Remmers et al., 2013; Roychowdhury and Dodds, 2002) or in the volume as 'continuum damage mechanics' (Gurson,1977; Kachanov, 1958; McClintock,1968; Rice and Tracey,1969). Till date, the application of these approaches has been confined primarily to macroscopically homogeneous materials. To the best of author's knowledge, any mature development that can deal with the additional parameters of weld strength mismatch ratio, weld geometry, etc. is yet to be made. Moreover, the structural integrity assessment of any real life component is still performed using the fracture mechanics based defect assessment procedures. This work has, thus, followed the conventional fracture mechanics approach to describe the effect of material mismatching on crack tip stresses, for a power-law hardening material model.

In this work a three-parameter scheme has been developed to estimate the crack tip stresses for fracture specimens having a weld center crack. A plastic interaction factor (I_p) is proposed that scales the size of the plastic zone with the width of the weld material. It represents the degree of influence of weld strength mismatch on crack tip constraint for a given mismatch ratio. The proposed scheme was validated with detailed FE analysis using the Modified Boundary Layer formulation. Wide range of mismatch ratio M varying from 0.6 to 1.6 was considered. Power-law hardening material model with strain hardening index ranging $n = 5$, and 10 were used in FE analysis.

2. Background

Crack tip stresses in homogeneous specimens can be described in terms of two parameters like K–T or J–Q (O'Dowd and Shih, 1991, 1992; Williams, 1957). While K and J account for the magnitude of applied load, the second parameter Q or T represents the crack tip constraint arising due to specimen geometry and type of loading. The T-stress, ahead of crack, in an elastic material can be derived using the power series expansion (Williams, 1957) as provided by the following equation

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}}\sigma_{ij}(\phi) + T\delta_{1i}\delta_{1j} \quad (1)$$

where K_I, is the elastic stress intensity factor and T, is a stress parallel to the crack face. T stress being an elastic parameter has no physical meaning under large scale plasticity. Q-stress proposed by O'Dowd and Shih(1991) is another way to describe the crack tip stresses in terms of J-integral (HRR field (Hutchinson,1968; Rice and Rosengren,1968)). Q stress is simply the deviation of crack tip stresses in an actual geometry from the reference HRR field.

$$\sigma_{ij} = (\sigma_{ij})_{HRR} + Q\sigma_o\delta_{ij} \quad (2)$$

where $(\sigma_{ij})_{HRR}$ is the crack tip stress distribution as obtained from HRR series and σ_o is the reference stress. Alternatively, Q stress parameter is defined as the difference of actual crack tip field from the $T = 0$ reference solution, as expressed below

$$\sigma_{ij} = (\sigma_{ij})_{T=0} + Q\sigma_o\delta_{ij} \quad (3)$$

Crack tip fields for $T = 0$ can be calculated by performing Modified Boundary Layer (MBL) analysis (Larsson and Carlsson,1973). MBL analysis is a concept from elastic fracture mechanics. It facilitates to characterize near tip stress field of an arbitrary crack geometry by disk-shaped finite element (FE) model by applying equivalent tractions or equivalent displacements on disk boundary, based on the first two terms of the Williams expansion Eq. (1).

Apart from specimen's geometry and type of loading, weld strength mismatch ratio (M) and weld geometry also affect the crack tip stresses in mismatched specimens (Kocak et al., 1988; Kirk and Dodd's, 1993; Michiba et al., 1994). Due to strength mismatch of base and weld material an additional constraint get developed at the tip of a crack lying in the weld region of a fracture specimen. In an overmatched specimen ($M > 1$), the plastic field easily penetrates into the base material and thus leads to a large plastic zone. As a result, the crack tip constraint in an overmatched weld gets relaxed. On the other hand, for an under-matched specimens ($M < 1$), the plastic field gets confined in the weaker weld material leading to much higher crack tip constraint. The load required for penetration of the plastic field into the base material also depends upon weld width, larger the weld width higher is the required load. To summarize, the crack tip constraint in a strength mismatched weld not only depends on the specimen's geometry and type of loading but also on strength mismatch ratio M and weld slenderness ratio. Burstow et al. (1998a) proposed a non-dimensional normalized load parameter $J/h\sigma_o$ (that relates the size of plastic zone, J/σ_o, with half of weld width, h) to incorporate the effect of magnitude of applied load and weld with on crack tip opening stress in mismatched specimens. For the case of $T = 0$ and a non-hardening material model, Burstow et al. (1998a) demonstrated that two different specimens having same mismatch ratio but subjected to different load levels and having different weld width would have nearly same crack tip opening stress provided the normalized load parameter is same for the two cases. It is well recognized that the T-stress has a strong influence on the plastic zone size (Larsson and Carlsson, 1973) ahead of crack tip. The validity of normalized load parameter, thus, needs to be studied for non zero T stresses due to its strong influence on the plastic zone size.

Apart from the problem of weld center crack, several investigations have been carried out to characterize near tip stresses for a crack lying at the interface of two different materials. Zhang et al. (1996, 1997) have suggested a two parameter formulation for characterizing near tip stress field of an interface crack. The first term represents the stress field obtained from HRR analysis for the (nominally) homogeneous material. The second term comprises of a mismatch constraint parameter M and an angular function which depends only on a function of the plastic hardening property of the reference material. M is a measure of the constraint caused by the material mismatch and is practically independent of the normalized distance from the crack tip.

3. Finite element analysis

In order to gain an insight of the influence of several variables affecting the crack tip opening stress in a strength mismatched weld, detailed 2-D finite element studies were carried out. The objective was to utilize the information gained from numerical analysis for developing a general scheme that can characterize