International Journal of Pressure Vessels and Piping 128 (2015) 69–83

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

Understanding and accounting for the effects of residual stresses on cleavage fracture toughness measurements in the transition temperature regime

R.G. Hurlston [a,*], J.K. Sharples [b], A.H. Sherry [a]

[a] School of Materials, The University of Manchester, Sackville Street, Manchester M13 9PL, UK
[b] Amec Foster Wheeler, Birchwood Park, Risley, Warrington WA3 6GA, UK

ARTICLE INFO

Article history:
Received 30 April 2014
Received in revised form
2 February 2015
Accepted 5 February 2015
Available online 12 February 2015

Keywords:
Residual stress
Cleavage fracture
Constraint
Local approach
Weld

ABSTRACT

Secondary self-balancing stresses exist in structural components due to manufacturing processes, e.g. welding. When a defect is present, such secondary stresses will influence both the local crack driving force and the level of crack-tip constraint. Fracture mechanics specimens machined from welded components can also retain significant residual stresses, and these can influence the measurement of fracture toughness. This paper describes the results of an experimental and numerical programme aimed as quantifying the effect of residual stresses on cleavage fracture toughness measured in deeply-cracked and shallow-cracked fracture mechanics specimens and with a view to correcting the resultant data. The results indicate that the influence of retained residual stresses on cleavage fracture toughness in such specimens can be characterised using two-parameter fracture mechanics.

1. Introduction

Good design and structural integrity assessments require account to be taken of residual stresses, which are often introduced during welding, particularly traditional welding methods such as submerged-arc welding used in the nuclear industry. Understanding regarding the effects of residual stresses on component behaviour under load can be improved; for example, how residual stresses affect the crack-tip constraint with varying defect size.

Research by Lewis et al. [1] has demonstrated the propensity for residual stresses to be retained in fracture mechanics specimens removed from welded components. The effect that these retained residual stresses have on the measured fracture toughness properties is not considered in the current British Standard En ISO 15653:2010 for the fracture toughness testing of metallic materials [2]. However, residual stresses can lead to problems attaining a straight fatigue crack front during pre-cracking of fracture mechanics specimens. In cases such as this, BS En ISO 15653:2010 recommends that, prior to pre-cracking, a 'stress relieving' procedure be carried out. The standard describes the protocol for the modification of residual stress conditions within specimens, which is aimed at ensuring that any residual stresses present in weld specimens are reduced to low and uniform levels, or at least to a state where an acceptably straight fatigue pre-crack can be grown. The standard suggests a number of methods by which this can be achieved. Local compression, where the ligament ahead of the machined notch is compressed [3], is the preferred method. However, the assumption that this successfully eradicates residual stresses has led to a number of analytical and experimental studies investigating its validity [4,5]. The results of these investigations suggest that, whilst local compression can reduce weld residual stresses in the ligament of the specimen, it can elevate the level of residual stress at the tip of the notch and also cause a significant modification to the level of triaxiality in the near-notch region.

It is clear from the existing literature that residual stresses can be retained in specimens extracted from welds, and that current BS En ISO 15653:2010 guidance [2] may not properly account for them. Residual stresses are either completely ignored if a straight fatigue pre-crack can be attained or modified, but not eradicated, if not. Research has shown that, in both of these cases, fracture toughness values can vary significantly (over 50%) from those of the 'real'

* Corresponding author.
E-mail addresses: robert.hurlston@manchester.ac.uk (R.G. Hurlston), john.sharples@amecfw.com (J.K. Sharples), andrew.sherry@manchester.ac.uk (A.H. Sherry).

http://dx.doi.org/10.1016/j.ijpvp.2015.02.001
0308-0161/

Nomenclature

a	crack length
a_n	notch length
B	specimen thickness
E	Young's modulus
J	domain integral (crack driving force)
J_c, K_{Jc}	apparent fracture toughness
J_c^*	material fracture toughness (under small-scale yielding conditions)
K_I	elastic stress intensity factor
K_J	stress intensity factor (converted from a domain integral)
n	material hardening coefficient
P_f	failure probability
Q	constraint parameter
r	distance from a crack-tip
r_c	characteristic distance from crack-tip (Ritchie, Knott and Rice local approach fracture parameter)
R	side punch radius
u	displacement
W	specimen width
x	distance between ligament and side punch
y	distance between notch tip and side punch
δ_{ij}	Kronecker's delta
ε	strain
ε_0	material yield strain
θ	angle relative to a crack
ν	Poisson's ratio
σ	stress
σ_0	material yield stress
σ_f	critical stress value (Ritchie, Knott and Rice local approach fracture parameter)
σ_{ij}	crack-tip stress field
σ_{ij}^*	small-scale yielding field

material fracture toughness as a result of residual stress induced modifications to both the crack driving force [6,7] and the level of crack-tip constraint [8–10].

Both geometry (including crack size) and loading mode are known to influence apparent fracture toughness levels in specimens and components. This so-called constraint effect arises when the level of stress triaxiality (the ratio of hydrostatic to von Mises equivalent stress) ahead of the crack-tip deviates from the small-scale yielding condition. Under such conditions, a single parameter, e.g. K or J, fails to properly characterise the crack-tip field. The effect of constraint is generally quantified by a second parameter; either T-stress, which is the second term of the Williams series expansion [11] for linear elastic crack-tip fields and represents the stress acting parallel to the crack plane on the flank of the crack, or the Q parameter, which provides a non-dimensional comparison between the crack-tip stresses in the component and those that would be expected under small-scale yielding conditions in elastic–plastic materials [12,13].

It is known that residual stresses can contribute to the driving force of cracks. However, their effect on the development of crack-tip fields during primary loading is less well understood. Recently, the effects of residual stresses and biaxial loading on constraint at crack-tips have been studied using various methods [8–10]. Xu and Burdekin [8] investigated the effects of residual stress induced triaxiality on constraint and fracture behaviour in 50D steel. The results of this analytical study were used to demonstrate that residual stresses acting on the crack-tip region can have the effect of either increasing or decreasing constraint, depending on the configuration of the residual stress state. Lee et al. [10] carried out similar work experimentally using A533B steel in the cleavage fracture regime, which further demonstrated the potential for residual stress in the crack-tip region to modify constraint and, hence, cleavage fracture toughness.

The complexity of the residual stress induced crack-tip stress fields and the associated plastic strain fields have caused difficulty when trying to characterise these effects using two-parameter J-Q fracture mechanics due to the challenge associated with identifying an appropriate reference stress field to use in the derivation of Q [10]. Given these difficulties, a novel method of introducing residual stresses with little or no associated plastic strain was developed by Mahmoudi et al. [14] whereby 'side punches' are used to compress material ahead of the crack, in the out-of-plane direction. Carefully considered punch configuration, positioning and displacement ensure that subsequent relaxation of the compressed material, after the punches have been removed from the specimen, generates significant crack-tip residual stress fields.

This paper is focused on the evaluation of the cleavage fracture toughness properties of ferritic pressure vessel steel welds where retained residual stresses in fracture mechanics specimens may have an impact on the stress, strain and displacement fields in the region surrounding a crack-tip. A combination of analytical and experimental work has been used to show how residual stresses can influence constraint without the crack-tip region being subjected to large plastic strains. Subsequently, a method is proposed whereby fracture toughness measurements derived from specimens that contain residual stresses could be corrected for their effect on crack driving force and crack-tip constraint. The paper first describes the nature of crack-tip fields and constraint based fracture mechanics. It proceeds to describe the experimental procedure that was undertaken, in which: (a) residual stresses were introduced into rectangular section single edge notch bend SEN(B) specimens using local out-of-plane compression, (b) deep and shallow cracks were inserted into the specimens to produce geometrically high and low crack-tip constraint conditions, and (c) the cracked specimens were loaded in three-point bending at −140 °C (to ensure cleavage fracture). The paper describes finite element analyses undertaken to characterise the stress fields ahead of the cracks in the mid-planes of the specimen cases and the values of J. J-Q loading lines for each case were produced. Finally, the paper uses the Ritchie, Knott and Rice (RKR) [15] model of cleavage fracture to assess the apparent fracture toughness behaviour of each specimen type. Comparisons between the experimental data and the finite element analyses are then drawn and conclusions presented.

1.1. Constraint based fracture mechanics

Constraint factors are used to characterise the differences between crack-tip fields relevant to small-scale yielding and 'real' components or specimens. For general crack-tip conditions, where small-scale yielding cannot be guaranteed, the stress field can be characterised as the sum of the small-scale yielding field