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Unified correlation of in-plane and out-of-plane constraint with fracture resistance of a dissimilar metal welded joint

J. Yang, G.Z. Wang *, F.Z. Xuan, S.T. Tu

Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

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ABSTRACT

In this study, the fracture resistance of a dissimilar metal welded joint was measured by single edge-notched bend specimens with different in-plane and out-of-plane constraints. Based on the area surrounded by the equivalent plastic strain isoline ahead of a crack tip (a unified constraint parameter), a unified correlation of in-plane and out-of-plane constraint with fracture resistance of the dissimilar metal welded joint with local strength mismatch was established. The results show that the unified constraint parameter can characterize combining constraint composed of in-plane, out-of-plane and material constraint (local strength mismatch).

1. Introduction

Constraint is the resistance of a structure against plastic deformation [1]. According to the crack plane, constraint can be divided into two conditions of in-plane and out-of-plane. The in-plane constraint is directly affected by the specimen dimension in the direction of growing crack, i.e. the length of the un-cracked ligament, whilst the out-of-plane constraint is affected by the specimen dimension parallel to the crack front, i.e. the specimen thickness. As constraint can significantly alter the material's fracture resistance, it is important to develop a clear understanding of its effect on the fracture behavior of material. Different fracture constraint parameters and theories, such as K–T [2], J–Q [3,4], J–A_2 [5] and T_Z [6–8], have been developed to characterize and analyze the constraint effect. These parameters were successfully used to quantify the in-plane or out-of-plane constraint separately. However, both in-plane and out-of-plane constraints generally exist in the actual engineering structures. In order to characterize both constraints together, Mostafavi et al. [9–12] have suggested a unified constraint parameter φ which was defined as the size of the plastic region at the onset of fracture normalized by the plastic region size of a standard test:

$$\varphi = \frac{A_c}{A_{ssy}} \tag{1}$$

where A_c is the plastic region area at fracture and A_{ssy} is the reference plastic region area at fracture for a standard specimen in plane strain condition. Unfortunately, the constraint parameter φ has its limitation in characterizing constraint at higher J-integral for ductile material with higher fracture resistance [13]. The authors in the previous study [13] defined a unified constraint parameter A_p by a modified the parameter φ as follows:

* Corresponding author. Tel.: +86 021 64252681; fax: +86 021 64253513.
E-mail address: gzwang@ecust.edu.cn (G.Z. Wang).

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Nomenclature

a	crack length
A_2	parameter quantifying second and third term of stress relative to the first term in a cracked elastic–plastic body
A_c	area of the plastic region at fracture
A_p	a new unified parameter for quantifying both in-plane and out-of-plane constraints
A_{PEEQ}	area surrounded by equivalent plastic strain isoline
A_{ref}	area surrounded by equivalent plastic strain isoline at fracture measured in a standard test
A_{ssy}	area of the plastic region at fracture measured in a standard test
B	specimen thickness
E	Young's modulus
h	weld semi-width
J	J-integral
J_C	fracture resistance characterized by J-integral
J_{ref}	fracture toughness measured in a standard test
K	stress intensity factor
M	a constraint parameter caused by material mismatch
Q	a constraint parameter under elastic-plastic condition
S	loading span
T	T-stress constraint parameter under elastic condition
T_Z	factor of the stress-state in 3D cracked body
W	specimen width
α	stain hardening coefficient in Ramberg–Osgood relation
β_g	a parameter by means of the T-stress to quantify geometrical constraint
β_m	a material constraint parameter
β_T	a total constraint parameter
ε_p	equivalent plastic strain
n	strain hardening exponent in Ramberg–Osgood relation
ν	Poisson's ratio
σ_0	yield stress
φ	a unified constraint parameter defined by plastic region area

Abbreviations

3D	three-dimensional
CCT	centre-cracked tension
CT	compact tension
DMWJ	dissimilar metal welded joint
FEM	finite element method
FZ	fusion zone
HAZ	heat affected zone
NIZ	near interface zone
PEEQ	equivalent plastic strain in ABAQUS code
SENB	single-edge notched bend
SENT	single-edge notched tension

$$A_p = \frac{A_{PEEQ}}{A_{ref}} \quad (2)$$

where A_{PEEQ} is the areas surrounded by the equivalent plastic strain (ε_p) isolines ahead of the crack tip and A_{ref} is the reference area surrounded by the ε_p isolines in a standard test. This unified constraint parameter has been indentified to be suitable for specimens with different in-plane and out-of-plane constraints (different crack depths a/W, different specimen widths W, different specimen thicknesses B and different loading configurations (SENB, CT, CCT and SENT)) [13,14]. A unified correlation line ($J_C/J_{ref} - \sqrt{A_p}$ line) of in-plane and out-of-plane constraint with fracture toughness of a steel was obtained [14]. However, the results mentioned above were only obtained from a homogeneous material (A508 steel). It is not clear that whether the unified correlation of in-plane and out-of-plane constraint with fracture resistance can be established by using the constraint parameter A_p for the dissimilar metal welded joints (DMWJs) with highly heterogeneous mechanical property (local strength mismatch).

The DMWJ is indispensable part of nuclear structures and has been widely used in primary water systems of pressurized water reactors in nuclear power plants. It is significant for accurate structural integrity assessment if the correlation of constraint with fracture resistance of different cracks in DMWJs was established and the constraint-dependent fracture