Materials and Design 68 (2015) 186–194

Contents lists available at ScienceDirect

Materials and Design

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

Effects of work hardening mismatch on fracture resistance behavior of bi-material interface regions

K. Fan, 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

ARTICLE INFO

Article history:
Received 8 October 2014
Accepted 18 December 2014
Available online 27 December 2014

Keywords:
Work hardening mismatch
Fracture resistance
Bi-material
Interface
Stress triaxiality

ABSTRACT

The finite element method based on GTN (Gurson–Tvergaard–Needleman) ductile damage mechanics model are used to investigate the effects of work hardening mismatch on fracture resistance behavior of two cracks (interface crack and near interface crack) in bi-material interface regions. The results under the simulation and investigation conditions in this work show that for the interface cracks, the material constraint effects caused by work hardening mismatches are detrimental for fracture resistance due to the increase of crack-tip stress triaxiality, and this detrimental effects increase with increasing the mismatch degree in work hardening. For the near interface cracks, the work hardening undermatching ($\Delta n > 0$, Δn is the difference in work hardening exponent between two materials) has beneficial effects on fracture resistance due to the decrease of crack-tip stress triaxiality, and the hardening overmatching ($\Delta n < 0$) has slight detrimental effects on fracture resistance. The work hardening mismatch also influences the crack growth paths, and the cracks generally propagate and deviate into the material sides with lower hardening capacity (higher hardening exponent n). In the integrity design and assessment for cracks in bi-material interface regions in dissimilar metal welded joints, it is recommended to obtain and use fracture resistance properties related to yield strength and work hardening mismatches.

1. Introduction

Dissimilar metal welded joints are widely used to join different metal materials in many engineering structural components, like pressure vessels and pipes. Nevertheless, the bi-material interface regions in such joints are usually indicated to be the weakest locations for failure due to the highly microstructure and mechanical heterogeneity. This heterogeneity will compromise the safe performance of the metal structures and could cause catastrophic accidents. Therefore, accurate structural integrity design and assessment for cracks in bi-material interface regions are very important.

For understanding the fracture resistance behavior of any welded structures containing cracks, the mismatches in mechanical properties is an important factor to be considered. The mismatches not only include the mismatch in yield strength (strength mismatch), but also mismatch in work hardening (plastic regions of the stress–strain curves beyond yielding) [1]. The strength mismatch is commonly defined by the ratio of the yield strengths of weld metal and base metal. This global strength mismatch has effects on the fracture mechanics crack driving force, crack-tip stress field, crack-tip constraint and fracture resistance, and has been widely investigated [2–8] and considered in the structural integrity assessment [9,10].

However, the work hardening mismatch is not widely investigated and considered in conventional assessment but plays a role in the determination of the fracture resistance and crack driving force [1]. In addition, the global strength mismatch only considers weld metal and base metal properties. For the bi-material interface regions in dissimilar metal welded joints, the global strength mismatch is difficult to define and a term 'local strength mismatch' in a more general way indicating the strength differences between the regions next to the crack has been proposed [1,11]. It has been shown in the previous studies of authors [11–16] and in the literature [17,18] that the local fracture resistance in conjunction with local material constraint effects and crack path deviation is strongly influenced by the 'local strength mismatch' in the bi-material interface regions in dissimilar metal welded joints. However, only a few studies on the effects of work hardening mismatch on crack-tip constraints, near tip stress fields and J-integral for bi-material interface cracks could be found in the literature [19–23]. Zhang et al. [19] introduced a material constraint parameter M to consider the effects of strength mismatch, plastic strain hardening mismatch and general mismatch on near-tip stress fields for bi-

* Corresponding author. Tel./fax: +86 21 64252681.
E-mail address: gzwang@ecust.edu.cn (G.Z. Wang).

http://dx.doi.org/10.1016/j.matdes.2014.12.031
0261-3069/

material elastic–plastic interface crack, and indicated that the *J*–*M* theory can be used in the assessment of fracture behavior of weldments with mismatches properties. Østby et al. [20] investigated constraint effect on the near tip stress fields due to difference in plastic work hardening for bi-material interface cracks in small scale yielding, and found that the change in stress depends strongly on hardening mismatch, increasing as the mismatch degree increases. The interfacial crack-tip constraints and *J*-integral for bi-materials with plastic hardening mismatch have been examined by Lee and Kim [21,22], and they have found that for bi-materials consisting of two elastic–plastic materials, increasing plastic hardening mismatch increases both crack-tip stress constraint in the lower hardening material and the *J*-contribution there. The influence of plasticity mismatch on the growth and coalescence of voids on the biomaterial interface was investigated by Li and Guo [23], and the results showed that the growth rate of the void on the biomaterial interface is much faster than in the homogeneous material and deformed voids are seriously distorted and the linking of adjacent voids takes place in the softer matrix material. However, the effects of work hardening mismatch on the local fracture resistance of bi-material interface and near interface cracks have not been investigated and understood.

Because of the complexity of strength and work hardening mismatches on the crack tip stress fields and fracture resistance behavior of welded joints, the trend is towards the application of damage mechanics models for computing the fracture resistance curve [1]. It is well known that the ductile crack initiation and growth in metals and welded joints are the result of nucleation, growth and coalescence of microvoids. For simulating this process, the damage mechanics model, such as the Gurson–Tvergaard–Needleman (GTN) model [24–26] was developed. This model has been widely used in simulating ductile crack growth and fracture resistance behavior for different specimens [27], material interfaces [17,27] and similar metal joints [28–32]. The fracture resistance curves of a dissimilar metal welded joint has also been simulated using the GTN model by authors [12]. This model may be used to systematically investigate and understand fracture resistance behavior of bi-material interface region cracks with different work hardening mismatches. In simulations, the work hardening properties of materials composed of the bi-material joints can be accurately changed, and other factors influencing fracture resistance also can be accurately controlled.

In this study, the finite element method based on GTN ductile damage mechanics model is used to investigate the effects of work hardening mismatch on fracture resistance behavior of two cracks (interface crack and near interface crack) in bi-material interface regions. The *J*–resistance curves and fracture toughness are calculated, and the results are analyzed by crack-tip stress triaxiality distributions. The structural integrity design and assessment for bi-material interface regions are also discussed.

2. Numerical simulation procedures

2.1. Materials

To investigate effects of work hardening mismatch on fracture resistance behavior of bi-material interface regions, two materials composed of the bi-material joint with the same elastic properties and yield strength but different plastic work hardening capacities are used. One material is the common ferritic low-alloy steel A508, which is usually used for making nuclear pressure vessels, and another material is assumed to have different work hardening exponent *n* which is denoted as A508-N. The true stress–strain relation of the two materials follows the Ramberg–Osgood form:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \quad (1)$$

where the ε and σ denote the true strain and the true stress, respectively. The σ_0 is tensile yield stress, ε_0 (=σ_0/E) is yield strain, E is Young's modulus, α is the Ramberg–Osgood coefficient, and n is the work hardening exponent. The A508 and A508-N materials have the same E = 202,410 MPa, Poisson's ratio ν = 0.3, σ_0 = 522 MPa and α = 3.89 at room temperature [33]. The work hardening exponent n of the A508 material is 7.04 [33], and that of the A508-N material is changed from 3.04 to 11.04. The true stress–strain curves of the A508-N materials with different n at room temperature are shown in Fig. 1 and the thick curve with n = 7.04 is the same as that of the A508 material.

2.2. Specimen geometry

The single edge-notched bend (SENB) specimens are used in FEM analyses. The loading configuration and geometry of the SENB specimen (L = 80 mm, S = 57.6 mm, W = 14.4 mm and a_0/W = 0.5) with bi-materials are illustrated in Fig. 2. The loading points and initial cracks are located at the centers of the specimens. For examining the effects of work hardening mismatch on fracture resistance behavior of bi-material interface regions and facilitating the interpretation of results, only the work hardening exponent n of the A508-N material is changed. The difference in work hardening exponent between A508-N and A508 ($\Delta n = n_{(A508\text{-}N)} - n_{(A508)}$) is defined as mismatch factor, and nine work hardening mismatch levels are simulated with (i) undermatched (work hardening capacities of A508 is lower than that of A508-N), Δn = −4, −3, −2 and −1; (ii) evenmatched (work hardening capacities of A508

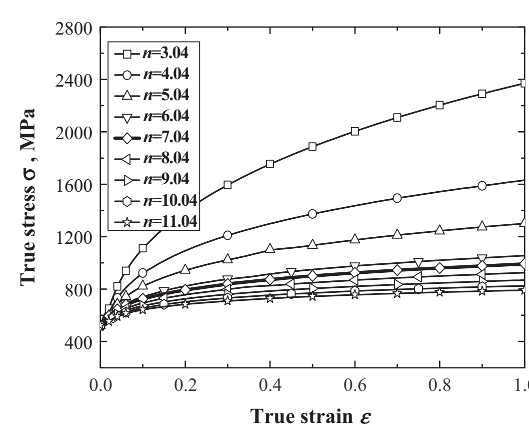

Fig. 1. True stress–strain curves of the A508-N materials with different work hardening exponents n at room temperature (the thick curve with n = 7.04 is that of the A508 material [33]).

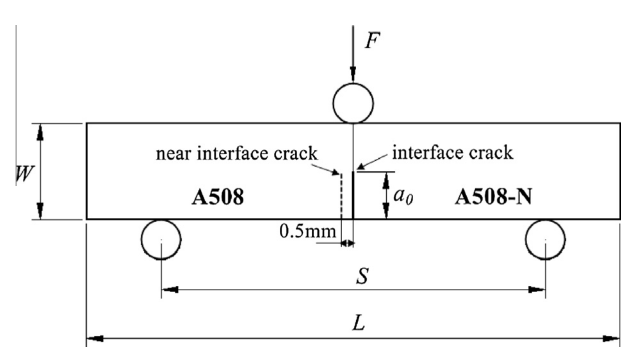

Fig. 2. The loading configuration and geometry of specimen.