MICROMECHANICAL STUDY OF DUCTILE FRACTURE INITIATION AND PROPAGATION ON WELDED TENSILE SPECIMEN WITH A SURFACE PRE-CRACK IN HEAT-AFFECTED ZONE (HAZ)

BASHIR SALEH YOUNISE¹, ALEKSANDAR STOJAN SEDMAK²

¹ University of El Mergib, Faculty of Engineering, Khoms, Libya. ² University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, Serbia

Abstract
In this paper, crack initiation and propagation was predicted in weldment using micromechanical approach and material properties determined by experimental and numerical procedure. Welded tensile specimen with a surface pre-crack in heat-affected zone (HAZ) was experimentally and numerically analyzed. High-strength low-alloyed steel was used as base metal, in quenched and tempered condition. Crack initiation values and J-R curves were obtained for specimen. The complete Gurson model (CGM) was used in prediction of J-R curve and crack growth initiation. The results show that the resistance to crack initiation and growth can be predicted using micromechanical analysis and material properties determined by experimental and numerical procedure.

1. Introduction
Crack initiation and stable growth in ductile materials are conventionally characterized by J-R curves obtained from standard fracture mechanics tests. However, testing of the same types of welded specimens (notched in different positions) and loading conditions revealed considerable differences in the J-R curves, due to the constraint caused by microstructural and mechanical heterogeneity [1-3]. Therefore, transferring fracture parameters from specimens to components is questionable. Constraint effect is very important in homogeneous structures, where the fracture resistance is dependent on geometry of the structure and the crack [4,5]. Moreover, recently produced high strength steel typically exhibit large-scale deformation and plastic straining during tearing. This helps to prevent rapid unstable fracture. However, such fracture behaviour cannot be accurately predicted using existing correlations that are characterized by J-integral. In the presence of large-scale yielding, the traditional J-integral approach to elastic-plastic fracture mechanics is known to become inaccurate or even inapplicable for engineering purposes as it cannot adequately characterize the crack tip stress field [6]. Therefore, more accurate characterizations of defects in welded high strength steels are of particular interest to provide more accurate failure assessments.

Using local damage approach to model crack initiation and propagation in ductile materials seems to be the solution for transferability problem in fracture mechanics. This approach can simulate the physical processes of void nucleation, growth and coalescence of investigated material using continuum mechanics. The complete Gurson model [7] has been shown to give accurate predictions for different levels of stress triaxiality, both for strain non-hardening and strain hardening materials, and is therefore selected to assess the fracture behaviour of welded joints in this work. Welded tensile specimens have been modelled; crack in the HAZ was considered. The aim of this work was to predict ductile crack initiation and propagation of high strength steel weldments using micromechanical model. Experimental work and three-dimensional finite damage model for welded tensile specimens with a pre-crack in HAZ was performed. Crack initiation value and J-R curve for tensile specimen with pre-crack have been obtained experimentally and numerically.

2. The complete Gurson model (CGM)
Micromechanical models have been recently developed for modeling the behavior of ductile materials. Among these models, micromechanical model proposed by Gurson is considered, as most widely used one for ductile porous materials. The yield function of Gurson [8], modified by Tvergaard [9,10] and Tvergaard and Needleman [11,12], is used to describe the evolution of void growth and subsequent macroscopic softening. The modified yield function is defined by formula:

\[ \psi(q_l, \sigma_t, \mathbf{f}) = \left( \frac{q_l}{\beta} \right)^2 + 2q_1 f^* \cosh \left( \frac{3q_3 \sigma_t}{2\beta} \right) - (1 + q_3 f^*)^2 = 0 \]

(1)

where \( \sigma_t \) is the mean stress, \( \sigma_t \) is the flow stress of the matrix material, \( f^* \) is the modified void volume fraction, and \( q \) is the von Mises effective stress:

\[ q = \sqrt{\frac{1}{2}} \sqrt{\sigma_{ij}S_{ij}} \]

(2)

where \( S_{ij} \) stand for the deviatoric components of Cauchy stress. The constants \( q_1 \) and \( q_2 \) are fitting parameters introduced by Tvergaard [9], to improve the ductile fracture prediction of Gurson model. The modified void volume fraction, \( f^* \), is the damage function [11]. More details about CGM model are given in [13].

1. Materials and experimental procedure
The material studied in this investigation was high strength low alloyed steel, NIMONIL 490K, which is used as the base metal. Shielded metal arc welding process (SMAW) was used with consumable VAC 60Ni to weld a plate (300 x 300 x 16 mm). A mixture of shielding gases; 3.8% CO₂+93.7% Ar+2.5% O₂, was used in order to get acicular ferrite, which raises toughness of welded joint. The estimated mechanical properties are given in Table 1 for base metal (BM), coarse heat-affected zone (CGHAZ), fine heat-affected zone (FGHAZ) and weld metal (WM). The Poisson’s ratio is assumed \( \nu = 0.3 \). More details are given in [13].
Quantitative microstructural analysis was performed to estimate the micromechanical parameters: volume fraction ($f_v$) and mean free paths ($\lambda$) between the non-metallic inclusions for the zones of the welded joint, according to [14] (Table 2). In the initial stage of ductile fracture of steel, the voids nucleate mostly around non-metallic inclusions. Hence, the initial porosity $f_0$ is here assumed to be equal to the volume fraction of non-metallic inclusions ($f_v$).

Table 1. Mechanical properties of used materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young modulus, $E$ [GPa]</th>
<th>Yield strength, $\sigma_y$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>202.9</td>
<td>520</td>
</tr>
<tr>
<td>CGHAZ</td>
<td>203</td>
<td>550</td>
</tr>
<tr>
<td>FGHAZ</td>
<td>195</td>
<td>500</td>
</tr>
<tr>
<td>WM</td>
<td>200</td>
<td>530</td>
</tr>
</tbody>
</table>

Table 2. Microstructural parameters of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$f_v$</th>
<th>$f_c$</th>
<th>$\lambda$ [\mu m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM (NIOMOL 490K)</td>
<td>0.0094</td>
<td>0.014748</td>
<td>578</td>
</tr>
<tr>
<td>HAZ</td>
<td>0.0086</td>
<td>0.014748</td>
<td>497</td>
</tr>
<tr>
<td>WM</td>
<td>0.0194</td>
<td>0.010685</td>
<td>202</td>
</tr>
</tbody>
</table>

4. Finite element models

For the determination of the value of stress and strain components and the value of damage parameter ($f$) in the specimens exposed to external mechanical loading, the FEM program Abaqus (www.simulia.com) was used, with CGM user subroutine, UMAT, developed by Zhang based on [7]. To simplify the finite element analysis, materials of all regions of welded joint were assumed to be isotropic. The mesh size, $l_c$, was chosen to approximate the mean free path between non-metallic inclusions. A fixed mesh size $l_c = 0.5$ mm of elements was chosen on vertical planes on the crack front of the tensile specimen with semi-elliptical surface crack in HAZ, but along the crack front is about $5$ $l_c$ because the variation of stress/strains in this direction is not significant (Figure 1).

In order to apply the CGM model to simulate the ductile tearing in tensile specimen with a pre-crack in HAZ, various model parameters must be determined:

The first set of constitutive parameters is $q_1$ and $q_2$, which related to the hardening of the matrix material. In this study, $q_1$ and $q_2$ were determined to be 1.2 and 1.0, respectively, for tensile specimen with a pre-crack in HAZ. The values of $q_1$ and $q_2$ were considered according to the study in [15]. The second set of parameters is void initiation and coalescence parameters ($f_0$, $f_c$ and $f_b$). Like mentioned previously, the initial void volume fractions ($f_0$) are assumed to be equal to the volume fraction of non-metallic inclusions ($f_v$), which is given in Table 2 for BM, HAZ and WM materials. The critical void volume fraction ($f_c$) is crucial damage parameter in CGM, since it represents the end of stable void growth and the start of void coalescence. It is not a material constant according to CGM, but it is automatically determined during the processing, based on the stress and strain fields. Void volume fraction at final fracture ($f_f$) is determined according to the relation $f_f = 0.15 + f_0$ [7], used in the complete Gurson model in the present study. The third set of parameters ($\varepsilon_{fc}$, $S_N$, and $f_b$) is related to void nucleation. The volume fraction of void nucleating particles ($f_b$) has been evaluated from Fe$_3$C content in materials. The nucleation parameters, $\varepsilon_{fc} = 0.3$ and $S_N = 0.1$ determined by Chu and Needleman [16, 17, 18], were considered for analysis model.

4.1. Numerical modeling of crack initiation

Crack initiation can be predicted by using the CGM model according to failure criterion. Failure is defined by the instant when the first element in front of the crack tip becomes damaged. The condition for the onset of the crack growth (as determined by the $J$-integral, $J_e$ or crack tip opening displacement, CTOD) is most adequately defined by the micromechanical criterion [19]:

$$f \geq f_c$$

(3)

when the condition given by Equation (3) is satisfied, the onset of the crack growth occurs. The critical void volume fraction ($f_c$) in CGM model is determined at the end of every increment step. To determine numerically crack initiation, the increase of void volume fraction ($f$) should be monitored at the nearest Gauss point to the crack tip. When current monitored $f$ reaches $f_c$ and Eq. (3) is satisfied, the fracture mechanics parameter at crack initiation ($J_e$ or CTOD) is determined.

The ductile growth initiation and propagation for tensile panels have been modelled as follows:

Ductile crack growth initiation described here by $J$-integral at initiation ($J_I$) is modelled for tensile panel with surface crack in HAZ based on critical void volume fraction criterion ($f_c$) which represents the end of stable void growth and the start of void coalescence in the material. The value of $J_I$ has been estimated numerically at the middle of the specimen thickness in front of crack line, where the highest value of void volume fraction occurs. The value of $J_I$ for tensile panel with surface crack in HAZ (TP-HAZ) is given.

Figure 1. Three-dimensional finite element model for tensile panel with surface crack in the HAZ: (a) 3D finite element mesh for half of specimen with boundary conditions, and (b) Detailed mesh for the region near the crack front.
in Table 3 in comparison with values of $J_i$ for SENB specimen with pre-crack in HAZ (SENB-WM) (See [13]). The $J_i$ of TP-HAZ was experimentally determined using stretch zone width, SZW according to [20].

Table 3. Numerical values of $J_i$ for tensile and SENB specimens with pre-crack in HAZ.

<table>
<thead>
<tr>
<th>Specimen designation</th>
<th>$J_{0.25 L}$ [N/mm]</th>
<th>$J_i$ [N/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Using SZW</td>
<td>CGM</td>
</tr>
<tr>
<td>SENB-HAZ</td>
<td>84</td>
<td>57</td>
</tr>
<tr>
<td>TP-HAZ</td>
<td>-</td>
<td>309</td>
</tr>
</tbody>
</table>

4.2. Numerical modeling of ductile crack propagation
Crack growth in ductile materials is conventionally characterized by fracture resistance curves, obtained from the standard fracture tests. However, these standard fracture tests introduce a high degree of conservatism in engineering critical assessment of real structures such as pressure vessels. Therefore, using specimens such as cracked tensile panels may present better integrity assessment.

$J$-R curve for HAZ has been numerically obtained using tensile panel with surface crack in HAZ. It has been simulated by tracing the path of completely damaged elements, which appear completely in different colours in this work (Figure 2). The element is assumed to be failed (completely lost its load carrying capacity) when the void volume fraction at final failure ($f_f$) is reached according to the relation $f_f = 0.15 + f_0$. Then, the corresponding value of $J$-integral is numerically obtained. The crack growth resistance curve is presented in Figure 3 for tensile panel with pre-crack in HAZ at the deepest point of the crack front for tensile panel where the largest crack growth occurs. The result has been compared with J-R curve for SENB specimen with pre-crack in HAZ which was obtained previously in [13] based on ASTM E1820-08. It is obvious that J-R curve obtained using SENB specimen is more conservative than one obtained using tensile panel.

Figure 2. Distribution of void volume fraction, which shows crack growth for tensile panel with surface crack in HAZ.

Figure 3. Comparison between experimental J-R curve of SENB specimen and numerical J-R curve of tensile panel with crack in HAZ.

5. Conclusion
The micromechanical complete Gurson model (CGM) was applied to estimate damage level (void volume fraction, $f_v$) in welded tensile specimen with a pre-crack in HAZ. True stress - true strain curves of the welded joint zones were determined by a combined experimental-numerical procedure, utilizing stereometric strain measurement and finite element modelling. Crack initiation value was successfully predicted using the CGM and true stress-true strain curves which were estimated by the experimental-numerical procedure. The results show that the constraint effect due to the geometry can be predicted as well.

References