Assessment of ductile fracture initiation in welded joints with two weld metals

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Keywords

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Introduction

The process of ductile fracture of most metals and alloys includes void nucleation, growth and coalescence. Void nucleation takes place around non-metallic inclusions and second-phase particles, and void nucleates when the so-called critical stress within the inclusion or at the inclusion-matrix interface is exceeded. With the increase of loading, these materials exhibit strain hardening, but also softening due to the presence of the voids.

Micromechanical models of local approach are often used for prediction of fracture initiation and development in steel and other metals and alloys. They are constantly being improved, with the main aim to offer an appropriate description of the macroscopic behaviour of the structure by modelling the damage on the micro scale.

According to the uncoupled approach to ductile fracture modelling, damage parameter is calculated by post processing routines. On the other hand, coupled approach incorporates the damage parameter into the numerical procedure, and its value is calculated during the finite elements (FE) analysis. Such models thus represent the material as a porous medium, taking into account the effect of voids on plastic flow and deformation.

Micromechanical modelling

The GTN (Gurson-Tveergard-Needleman) model describes nucleation and growth of voids through an extension of von Mises plasticity theory, [1]-[3]. In this model, the void volume fraction or porosity f is incorporated as the damage parameter into the plastic potential expression:

$$\phi = \frac{3S_{ij}S_{ij}}{2\sigma^2} + 2q_1 f^* \cosh\left(\frac{3q_2\sigma_m}{2\sigma}\right) - \left[1 + \left(q_1 f^*\right)^2\right] = 0 \quad (1)$$

σ is current yield stress of the material matrix, σ_m is mean stress, S_{ij} is stress deviator, q_1 and q_2 are parameters (Tvergaard, [2]), while f^* is the damage function [3]:

$$f^* = \begin{cases} f & \text{for } f \le f_c \\ f_c + K(f - f_c) & \text{for } f > f_c \end{cases} \quad (2)$$

f_c is the critical porosity - corresponding to the onset of the void coalescence. The parameter K is often called the accelerating factor and describes the sudden loss of the load carrying capacity during the final stage of ductile fracture until its final failure.

The plastic limit load model (Thomason, [4]) for void coalescence is used by Zhang et al [5] to improve the treatment of void coalescence in GTN model. This way, the complete Gurson Model - CGM is proposed. The criterion for the onset of the void coalescence is:

$$\frac{\sigma_1}{\sigma} > \left(\alpha\left(\frac{1}{r} - 1\right) + \frac{\beta}{\sqrt{r}}\right)\left(1 - \pi r^2\right) \quad (3)$$

where σ_1 is the maximum principal stress, α and β are constants introduced by Thomason [4], and r is the void space ratio [5], given by:

$$r = \sqrt[3]{\frac{3f}{4\pi} e^{\varepsilon_1+\varepsilon_2+\varepsilon_3}} \Bigg/ \left(\frac{\sqrt{e^{\varepsilon_2+\varepsilon_3}}}{2}\right) \quad (4)$$

in this expression, ε_1, ε_2 and ε_3 stand for the principal strains. The approach described in [5] lead to the fact that critical porosity f_c is not a material constant in the CGM - but the material response to void coalescence during the increase of loading.

Investigation of welded joints

The analysis of the crack growth initiation is conducted on high-strength low-alloyed (HSLA) steel welded joints. The base metal (BM) is HSLA steel NIOMOL 490 and the joints are fabricated using two different filler materials - to obtain overmatched, OM, and undermatched, UM, weld metals with a sharp interface between them. Yield strengths are: 545 MPa for BM, 648 and 455 MPa for the OM and UM weld metals, respectively. Microstructural parameters - the volume fraction of non-metallic inclusions f_v and mean free path between them λ are determined by quantitative microstructural analysis, according to ASTM E1245. The values of these parameters for all the three materials (BM, OM and UM) can be found in [6], and it is observed that they are not much different for the two weld metals (the cracks in all specimens are located in the weld metal).

Single-edge notched bend (SENB) specimens are used for examination of welded joints. Dimensions of the specimens are $W \times B \times L$ = 25×25×125mm, with distance between the supports 100mm. The width of the joint is 10mm.The initial crack lies on the symmetry axis of the joint, and is perpendicular to the OM/UM interface. Ductile fracture initiation is analysed using the single-edge notched bend (SENB) specimens. These joints are composed of two weld metals, undermatched (UM) and overmatched (OM), as shown in Figure 1, and are denoted as double mismatched

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(DM) joints. They are often used for repair welding, where the filler material for repair is not the same as that for initial fabrication (welding). Also, their application includes welding of HSLA steels, because it enables the manufacturing of a joint without preheating, reducing the production costs.

The main aim in this paper is estimating the constraint effect caused by the different initial crack length in analysed welded joints with two weld metals. Of course, due to the geometry of the joints, changing of a_0 for the constant thickness of the OM/UM portions of the joint (Figure 1, widths of the two parts are equal) also causes the change of distance between the interface and the crack tip, L. Micromechanical models are a very good tool for the analysed configuration, because they can naturally take into account the geometry of the cracked structure - without a need to introduce some additional parameters that would describe the constraint effect. For this type of joints, there are no solutions in commonly used structural integrity assessment procedures (like SINTAP/FITNET, etc.). A contribution to analysis in that framework is presented in [7], where the influence of the crack length and mismatch ratio is estimated by the yield load solutions - development of plasticity through the entire ligament in front of the crack tip.

In the presented investigation, the specimens are analysed under plane strain conditions, and the finite element (FE) mesh consists of 4-noded or 8-noded elements with 2×2 integration. The mesh of the region around the crack tip is shown in Figure 1.

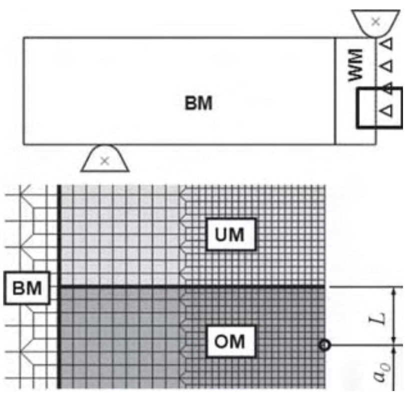

Figure 1. Model of welded SENB specimen and FE mesh for joints with two weld metals

FE software package ABAQUS (www.simulia.com) is used for numerical analysis and the CGM is applied through user material subroutine created by Zhang, based on [5]. The initial porosity is taken as equal to volume fraction of non-metallic inclusions f_v, since the voids nucleate mostly around these inclusions in the initial stage of ductile fracture of steel. FE size near the crack tip is 0.15×0.15 mm (corresponding to the mean free path between the inclusions in WM, according to [8], [9]).

Crack tip opening displacement (CTOD) values are determined, both experimentally and in numerical calculations, using δ_5 concept. CTOD value at the onset of the crack growth (denoted as $CTOD_i$) is determined from the condition that damage parameter f has to reach its critical value f_c at the integration point nearest to the crack tip.

Results and discussion

Distribution of von Mises stress in the welded joint at the onset of the crack growth is shown in Figure 2. It can be seen that, besides in the vicinity of the crack tip in the OM weld, plasticity spreads to the UM part of the joint as well (three darkest colors in Figure 2 correspond to the yield stresses of the OM, BM and UM, respectively).

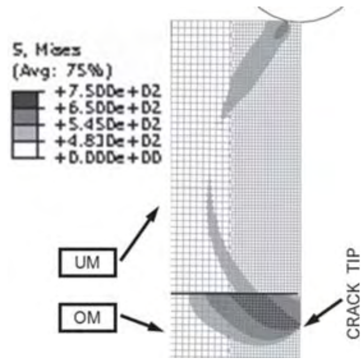

Figure 2. Distribution of von Mises equivalent stress at the onset of the crack growth

Figure 3 presents the distribution of porosity f (denoted as VVF in the figure) at the onset of the crack growth. It can be seen that it is strictly localized in the area near the crack tip. Of course, if the crack growth is modelled using coupled approach to ductile fracture, by damaging the elements in front of the crack tip (without releasing the nodes), the advance of the large f values through the ligament will represent the growth of the crack.

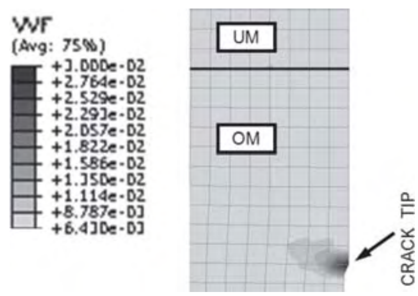

Figure 3. Distribution of porosity at the onset of the crack growth

The influence of the initial crack length on prediction of the crack growth initiation using the CGM is given in Figure 2. Calculation with 4-noded elements gives somewhat higher values in comparison with 8-noded for the same number of integration points, especially for shorter cracks. Decrease of $CTOD_i$ values with increase of a_0/W ratio (W stands for the entire width of SENB specimen, and is comprised of two equal parts - OM and UM, as mentioned before) is observed. The decrease of $CTOD_i$ in the vicinity of the interface slows down - nearly constant $CTOD_i$ values are obtained in the range $0.4 < a_0/W < 0.5$. A comparison with the experimental results is given for some examined configurations, i.e. for different crack lengths of the examined specimens. However, it should be noted that determination of these values (corresponding to ductile fracture initiation) is very often prone to some level of uncertainty. Bearing these facts in mind, obtained results will be used as a starting point for forming the J-Δa curves, i.e. determining the crack growth resistance - which should provide a better description of the fracture behaviour of the examined joints.

The influence of the sharp interface between the two weld metals can be seen if the plots in Figure 4 are compared with the results obtained by testing the joints with single (overmatched) weld metal, Figure 5. It can be seen that $CTOD_i$ values obtained by the CGM decrease with the increase of a_0/W, which is also observed during the experimental investigation of two specimens with different initial crack lengths. These specimens (OM) had different joint width (6 mm, while DM joints were 10 mm wide), so the values cannot be compared directly. Nevertheless, the difference in trend between these two cases, DM vs. OM, is obvious.

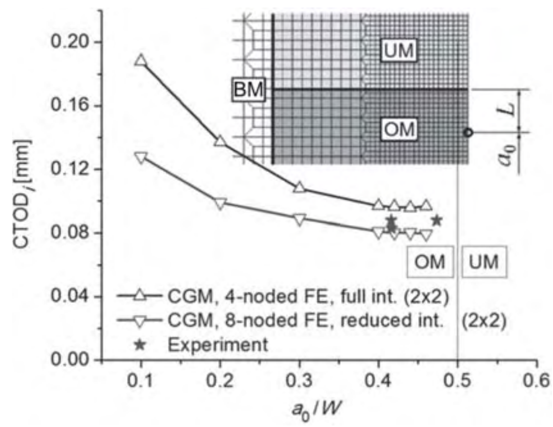

Figure 4. Influence of initial crack length a_0 on $CTOD_i$ for joints with two weld metals

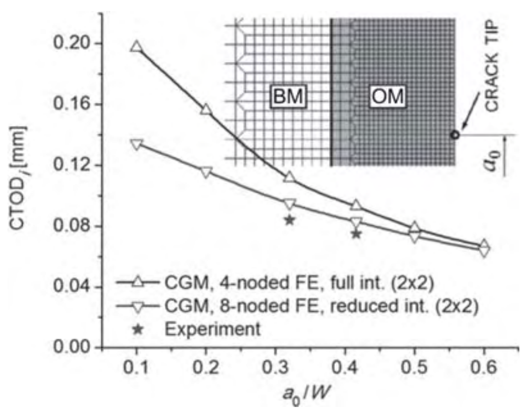

Figure 5. Influence of initial crack length a_0 on $CTOD_i$ for joints with one weld metal

Another aspect should be taken into account if the crack tip is very close to the OM - UM interface (i.e. when the distance L is very small, Figure 1b, or even when the crack has already passed through the interface). In that case, shielding or anti-shielding effect on crack driving force occurs, [10], [11]. Therefore, determining of this influence (of a sharp inhomogeneity) on the micromechanical modelling of ductile fracture initiation and development in such structures is one of the directions of the future research.

Conclusions

It is concluded that ductile fracture initiation in analysed welded joints can be modelled using the complete Gurson model. The effect of constraint for cracks perpendicular to the interface between the two weld metals is correctly predicted. Comparison with the joints fabricated using one filler material reveals that the interface contributes to a slower decrease of crack initiation resistance with the increase of the crack length. Interpolation order has an influence on the results (for the same number of integration points). The difference in results obtained with 4-noded and 8-noded elements is larger for shorter cracks.

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References

[1] Gurson, A., "Continuum theory of ductile rupture by void nucleation and growth: Part I - yield criteria and flow rules for porous ductile media", J. Engin. Mater. - T. ASME, vol. 99, 1977, pp. 2-15.

[2] Tvergaard, V., "Influence of voids on shear band instabilities under plane strain conditions", Int J Fract, vol. 17, 1981, pp. 389-407.

[3] Tvergaard, V. and Needleman, A., 1984, "Analysis of Cupe-Cone Fracture in a Round Tensile Bar," Acta Metall, vol. 32, 1984, pp. 157-169.

[4] Thomason, P.F., Ductile Fracture of Metals, Oxford: Pergamon Press, 1990.

[5] Zhang, Z.L., Thaulow, C. and Ødegård J., "A complete Gurson model approach for ductile fracture" Eng. Fract. Mech., vol. 67, 2000, pp. 155-168.

[6] Medjo, B., Rakin, M., Gubeljak, N., Arsiç M. and Sedmak A., "Local approach to analysis of ductile fracture in welded joints - influence factors", accepted - 18th European Conference on Fracture ECF18, Dresden, 2010.

[7] Kozak, D., Gubeljak, N., Konjatiç, P. and Sertiç, J., "Yield load solutions of heterogeneous welded joints" Int J Pres Ves Pip, vol. 12, 2009, pp. 807-812.

[8] Rakin, M., Cvijoviç, Z., Grabulov, V., Putiç, S. and Sedmak, A., "Prediction of ductile fracture initiation using micromechanical analysis" Eng Fract Mech, vol. 71, 2004, pp. 813-827.

[9] Medjo, B., Rakin, M., Gubeljak, N. and Sedmak, A., "Application of complete Gurson model for prediction of ductile fracture in welded steel joints" Key Eng. Mater., vol. 399, 2009, pp. 13-20.

[10] Predan, J., Gubeljak, N. and Kolednik, O., "On the local variation of the crack driving force in a double mismatched weld" Eng Fract Mech, vol. 74, 2007, pp. 1739-1757.

[11] Rakin, M., Kolednik, O., Medjo, B., Simha, N.K. and Fischer, F.D., "A case study on the effect of thermal residual stresses on the crack-driving force in linear-elastic bimaterials", Int J Mech Sci, vol. 51, 2009, pp. 531-540.

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