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Numerical Simulation for Studying Constraint Effect on Ductile Fracture Initiation Using Complete Gurson Model

Ductile fracture initiation in high-strength low alloyed welded steel joints is predicted using micromechanical complete Gurson model (CGM). The crack tip constraint and variation of stress triaxiality in ligament are considered on single-edge notch bend SE(B) and compact tension C(T) specimens, including the effect of strength mismatching and different weld metal width. According to the analysis of stress triaxiality in front of the crack tip, transferability of fracture initiation parameter was studied. As a result of the analyses on specimens, fracture initiation parameter determined by using CGM can be transferred from one geometry to another if their triaxial conditions are found to be similar.

Keywords: *ductile fracture, transferability, constraint effect, welded specimens.*

1. INTRODUCTION

Ductile fracture is a geometry dependent event, whereas the fracture toughness or ductility of a material can not be directly transferred from one geometry to another. It depends on variation of geometry constraint level, therefore conventional fracture mechanics parameters, such as J or $CTOD$ can be used only in some limited cases. Ductile fracture process is controlled by nucleation, growth and coalescence of micro voids, so it is natural to link material fracture behaviour to the parameters that describe the evolution of micro voids rather than conventional global fracture parameters. Numerous micromechanical models have been developed to describe the behaviour of ductile materials. They are classified into two main groups: uncoupled and coupled micromechanical models. In uncoupled ones, such as Rice and Tracey [1] and McClintock [2], failure stage is characterized by the critical void growth ratio $(R/R_0)_c$, corresponding to the crack initiation. Damage parameter is not incorporated into the constitutive equation and it is assumed that presence of voids does not significantly alter the behaviour of the material. The von Mises criterion is most frequently used as yield criterion in uncoupled models, while coupled models, such as Rousselier [3] and Gurson [4] are recently more interesting for researchers. Damage parameter is incorporated into constitutive equation and crack growth simulation is automatically performed using a complete deterioration of elements in front of the crack tip [5]. One of the most widely used models is Gurson model for ductile porous materials. It was improved later by Tvergaard and Needleman [6] and is known as Gurson-Tvergaard-Needleman (GTN) model.

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This model has incorporated damage parameter (void volume fraction) in flow criterion and it considers the critical void volume fraction, f_c, as a material constant-failure parameter. The GTN model has been further upgraded by Zhang [7], who introduced the complete Gurson model (CGM). This model does not consider the critical void volume fraction, f_c, as a material constant, but as a variable which depends on stress/strain state, constraint level, etc.

In this paper, the effect of the weld metal width and strength mismatching on ductile fracture initiation have been investigated by using the complete Gurson model (CGM). Numerical simulation of two different welded specimens; single-edge notch bend, SE(B), and compact tension, C(T), was done. The two welded specimens were made of high-strength low alloyed (HSLA) steel. They have been used to study constraint effect on over-matched (OM) and under-matched (UM) welded joints. Transferability of ductile fracture initiation parameter between the two specimens has also been discussed.

2. DUCTILE TEARING MODELLING

Micromechanical models have been recently developed for modelling the behaviour of ductile materials. Among these models, micromechanical model proposed by Gurson is considered, as most widely used one for ductile porous materials. Gurson has derived yield condition equation for porous plastic solids. He analyzed a spherical void in an infinite perfectly plastic medium. Tvergaard and Needleman [6] have modified this model and derived the following yield condition known as Gurson-Tvergaard-Needleman (GTN) model:

$$\Phi\left(\sigma,\sigma_{\mathrm{eq}},f\right)=$$
$$=\frac{\sigma_{\mathrm{eq}}^2}{\sigma_{\mathrm{y}}}+2f^*q_1\cosh\left(\frac{3}{2}q_2\frac{\sigma_{\mathrm{m}}}{\sigma}\right)-\left[1+q_3\left(f^*\right)^2\right]=0 \quad (1)$$

where $\sigma_{eq} = \sqrt{(3/2)S_{ij}S_{ij}}$; S_{ij} is the stress deviator; σ denotes the current yield stress of the material matrix; σ_m is the mean stress; q_1 and q_2 are the constitutive parameters introduced by Tvergaard [8] to improve the ductile fracture prediction; $q_3 = (q_1)^2$ and f^* is the damage function [6] defined by:

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

where f_c is the critical void volume fraction corresponding to the occurrence of void coalescence; the parameter K is the accelerating factor which defines the slope of a sudden drop of force on the force – diameter reduction diagram.

The damage parameter f is evaluated by equation which consists of two terms describing the nucleation and growth of voids under the external loading:

$$\dot{f} = \dot{f}_{\text{nucleation}} + \dot{f}_{\text{growth}} . \tag{3}$$

Nucleation is considered to depend exclusively on the effective strain in the material and can be estimated by the following equation:

$$\dot{f}_{\text{nucleation}} = A\dot{\varepsilon}^p_{\text{eq}} \tag{4}$$

where $\dot{\varepsilon}^p_{\text{eq}}$ is the equivalent plastic strain rate; parameter A is a scalar constant concerning the damage acceleration. It is estimated by the following expression:

$$A = \frac{f_N}{S_N\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\varepsilon_{\text{eq}} - \varepsilon_N}{S_N} \right)^2 \right] \tag{5}$$

where f_N is volume fraction of void nucleating particles, ε_N is the mean void nucleation strain and S_N is the corresponding standard deviation; fitting parameters of the yield function of Gurson.

The micro void volume fraction due to growth can be estimated by:

$$\dot{f}_{\text{growth}} = (1 - f)\,\dot{\varepsilon}^p_{\text{ii}} . \tag{6}$$

where $\dot{\varepsilon}^p_{\text{ii}}$ is plastic part of the strain rate tensor.

The critical void volume fraction, f_c, is not considered as a material constant. It is determined by Thomason's plastic limit-load criterion, which predicts the onset of coalescence when the following condition is satisfied [9]:

$$\frac{\sigma_1}{\sigma} > \left(\alpha\left(\frac{1}{r} - 1 \right) + \frac{\beta}{\sqrt{r}} \right)\left(1 - \pi r^2\right) \tag{7}$$

where $\alpha = 0.1$ and $\beta = 1.2$ are two constants fitted by Thomason, σ_1 is the maximum principal stress and r is the void space ratio given by the formula:

$$r = \sqrt[3]{\frac{3f}{4\pi} e^{\varepsilon_1 + \varepsilon_2 + \varepsilon_3}} \left(\frac{\sqrt{e^{\varepsilon_2 + \varepsilon_3}}}{2} \right)^{-1} \tag{8}$$

where ε_1, ε_2 and ε_3 are the principle strains.

The complete Gurson model was implemented into the finite element code ABAQUS through the material user subroutine UMAT, which has been developed by Zhang, based on [7].

3. MATERIAL

Two different specimens, SE(B) and C(T), were used to test the fracture initiation in over-matched (OM) and under-matched (UM) welded joints. The joints were made of HSLA steel. Mechanical properties and chemical composition of used materials are given in Tables 1 and 2, respectively. Two weld metal widths (6 and 18 mm) were used. The mismatching factor M is defined as the ratio of the yield strength of the weld metal and the base metal:

$$\text{M} = \frac{R_{P0.2\text{WM}}}{R_{P0.2\text{BM}}} \tag{9}$$

where $R_{P0.2\text{WM}}$ and $R_{P0.2\text{BM}}$ are yield strengths of the weld and base metal, respectively.

Table 1. Mechanical properties of base metal and weld metals at room temperature

Material	E [GPa]	$R_{p0.2}$ [MPa]	R_m [MPa]	M
Over-matching	183.8	648	744	1.19
Base metal	202.9	545	648	–
Under-matching	206.7	469	590	0.86

The parameters of the GTN model such as initial void volume fraction (f_0), etc, summarized in Table 3, were obtained previously in [10]. The effect of secondary voids on ductile fracture was neglected, because the secondary voids formed around Fe_3C particles have extremely low effect and are present only during the final stage of ductile fracture.

4. NUMERICAL MODELLING

Mechanical properties were determined at room temperature. True stress – true strain data, given in Figure 1, was used in numerical modelling. The welded specimens in Figures 2 and 3, with the ratio of crack length to specimen width $a_0 lW = 0.32$ and thickness 25 mm, were modelled. The geometry of SE(B) specimen is given in [10].

Table 2. Chemical composition of base metal and fillers in weight %

Material	C	Si	Mn	P	S	Cr	Mo	Ni
Filler: over-matching	0.04	0.16	0.95	0.01	0.02	0.49	0.42	2.06
Base metal	0.123	0.33	0.56	0.003	0.002	0.57	0.34	0.13
Filler: under-matching	0.096	0.58	1.24	0.013	0.16	0.07	0.02	0.03

Table 3. Parameters of the GTN model for the weld metals [10]

Material	f_0	f_N	q_1	q_2	q_3
OM-WM	0.002	0	1.5	1	2.25
UM-WM	0.002	0	1.5	1	2.25

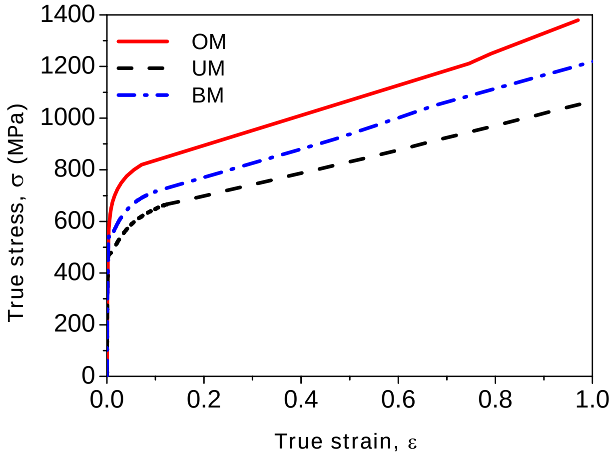

Figure 1. True stress – true strain curves of tested materials

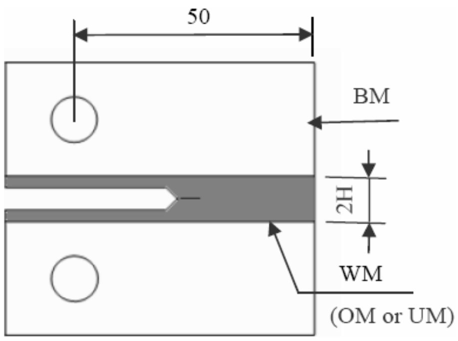

Figure 2. Geometry of welded C(T) specimen

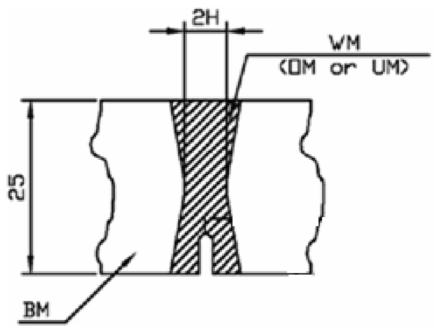

Figure 3. Welded joint of SE(B) specimen

Welded specimens are considered as bimaterial joints, since the crack is located in the weld metal, along the axis of symmetry of the weld. Two different widths of weld metal for both OM and UM welded joints were used: $2H = 6$ and 18 mm.

The FEM program ABAQUS was used with CGM user subroutine for determination of the value of stress and strain components and the value of f during the increase of loading. The specimens were analysed under plane-strain conditions, and 8-noded isoparametric reduced integration elements were used. The FE size (0.15 mm × 0.15 mm) which approximates the estimated value of the mean free path λ between non-metallic inclusions was used for both specimens (Fig. 4). The FE mesh of SE(B) specimen is given in [10]. Due to the symmetry of SE(B) and C(T) specimens, half of each specimen was modelled.

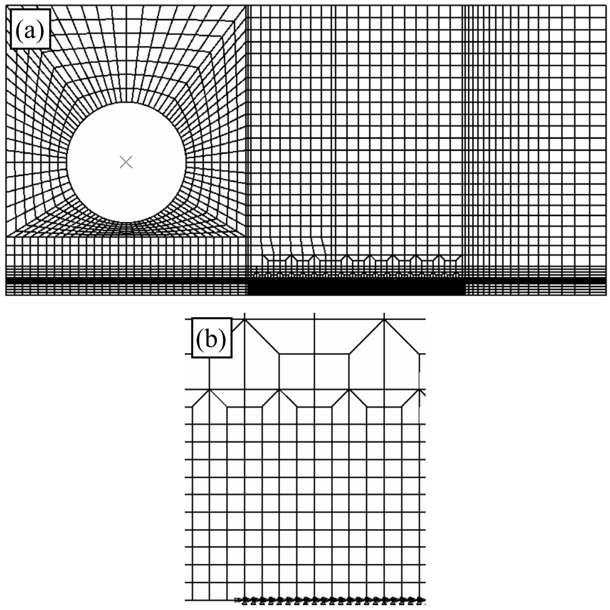

Figure 4. FE mesh of: (a) C(T) specimen and (b) detail of crack tip mesh

5. RESULTS AND DISCUSSION

5.1 Prediction of ductile fracture initiation

The effect of strength mismatching and width of the weld metal on fracture can be predicted successfully by using the CGM. Crack growth initiation was predicted using the critical void volume fraction, f_c, as a 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 crack growth, as determined by the J-integral (or $CTOD$) at initiation, J_i ($CTOD_i$), is most adequately defined by the micromechanical criterion [10]:

$$f > f_c . \tag{10}$$

When the condition given by (10) is satisfied, the onset of the crack growth occurs. Ductile fracture initiation is described here by crack tip opening displacement ($CTOD_i$) value at crack growth initiation. The $CTOD_i$ was estimated by complete Gurson model when the critical void volume fraction (f_c) is reached.

The results are given in Table 4, and it can be seen that the numerical results for $CTOD_i$ are in good agreement with experimental ones especially in UM welded joints, while it is not the case in OM welded joints. The reason may be due to considering mechanism of ductile fracture for OM welded joints, which probably exhibits a small fraction of cleavage.

Figures 5 and 6 show damage parameter (f) versus $CTOD$ for C(T) and SE(B) specimens in case of over-matched and under-matched welded joints. In Figure 5, it is pronounced that increasing rate of damage parameter in case of wider weld metal ($2H = 18$ mm) is higher than increasing rate of damage parameter in case of narrow one ($2H = 6$ mm) for OM welded joints, while the opposite phenomenon was observed in case of UM welded joints (Fig. 6).

Table 4. Experimental and numerical values of *CTOD*$_i$ for SE(B) and C(T) specimens in OM and UM welded joints

Specimen type		$CTOD_i$ [mm]			
		$2H$ = 6 mm		$2H$ = 18 mm	
		Exp.	Num.	Exp.	Num.
SE(B)	OM	0.084	0.157	0.065	0.129
	UM	0.120	0.119	0.132	0.130
C(T)	OM	–	0.094	–	0.089
	UM	–	0.086	–	0.092

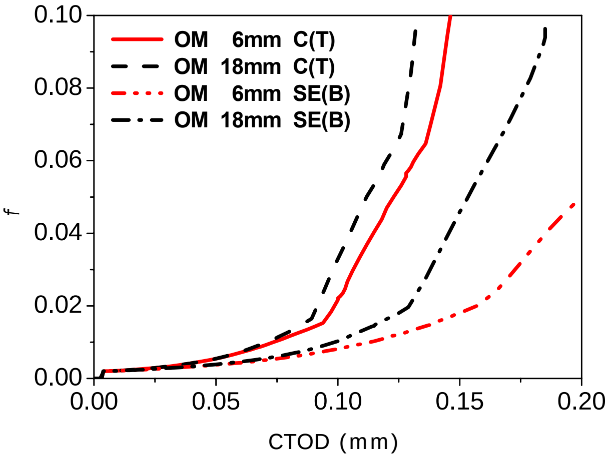

Figure 5. Crack tip opening displacement (*CTOD*) vs. void volume fraction (*f*) for OM welded joints

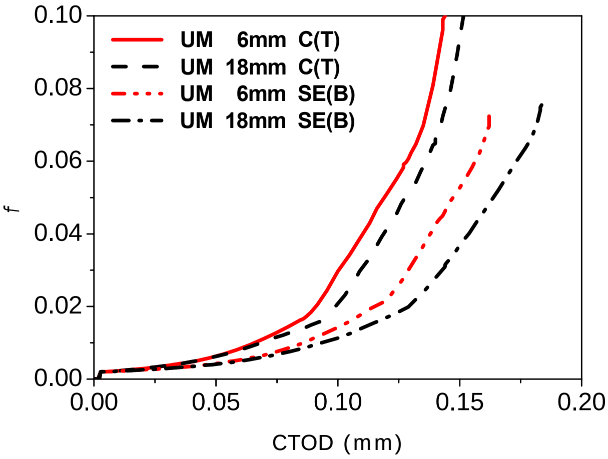

Figure 6. Crack tip opening displacement (*CTOD*) vs. void volume fraction (*f*) for UM welded joints

This phenomenon is in good agreement with experimental results given in [11], which show that smallest weld metal width in OM welded joints has the highest resistance to ductile fracture initiation, while the opposite behaviour was obtained for UM welded joints. Moreover, the effect of weld metal width on resistance to ductile fracture initiation for over-matched C(T) welded specimen is lower than the effect of weld metal width on that for over-matched SE(B) specimen (Fig. 5). It is apparent, the C(T) specimen is more conservative than SE(B) specimen.

5.2 Evaluation of constraint level

To compare the stress triaxiality of specimens or components, one should take in account the remaining ligament which should be considered. Some investigations [12] indicated that the specimens for structural integrity assessment can be selected according to constraint level. If the constraint level of specimen matches the constraint level of component, the results of specimen seem to be transferred to that component within certain circumstances.

The effect of the specimen geometry, strength mismatching and weld metal width on ductile fracture initiation was evaluated on the base of stress triaxiality in front of crack tip. Figures 7, 8 and 9 illustrate variation of stress triaxiality due to the variation of specimen geometry with loading conditions, strength mismatching and width of the weld metal, respectively.

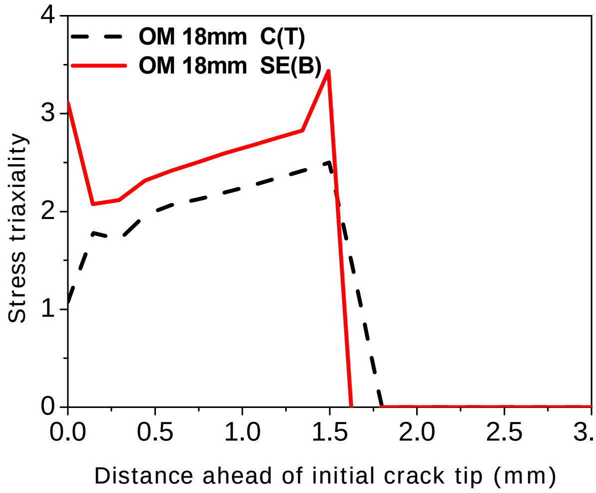

Figure 7. The effect of specimen geometry with loading conditions on stress triaxiality in front of the crack tip

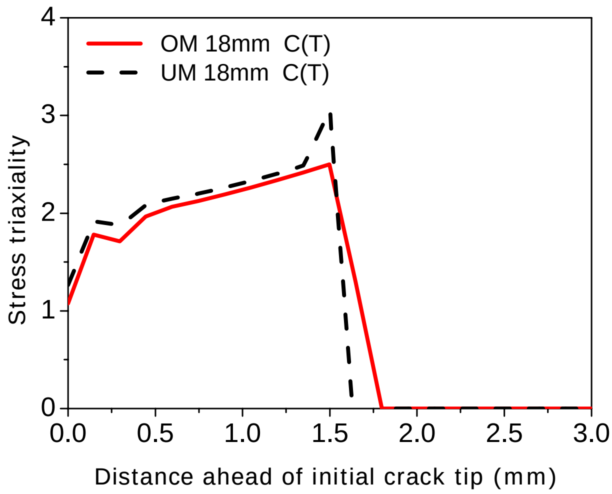

Figure 8. The effect of strength mismatching on stress triaxiality in front of the crack tip

One can notice, the geometry of specimen with loading conditions (Fig. 7) has the most pronounced influence on ductile fracture initiation in comparison with the influence of strength mismatching (Fig. 8) and weld metal width (Fig. 9). The least pronounced influence on ductile fracture initiation is obtained for the weld metal width. As the result, the best resistance to ductile fracture initiation can be obtained according to the best combination among structure geometry, strength mismatching and weld metal width.

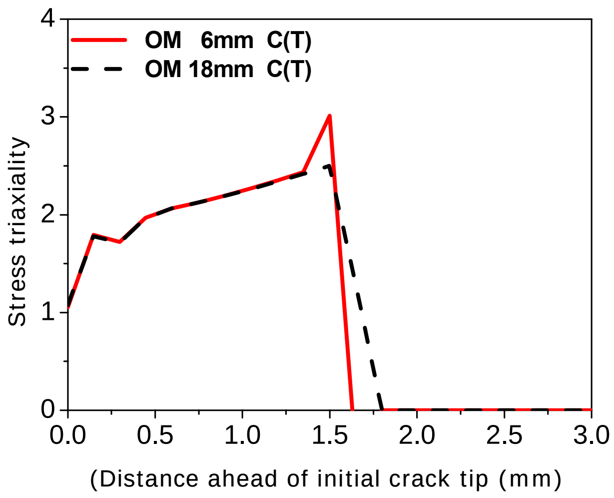

Figure 9. The effect of weld metal width on stress triaxiality in front of the crack tip

6. CONCLUSION

Constraint effect on ductile fracture initiation in welded specimens made of high-strength low alloyed steel has been studied using a complete Gurson model (CGM). Two different welded specimens, SE(B) and C(T), were used to predict ductile fracture initiation and the effect of structure geometry, strength mismatching and weld metal width. The following conclusions are drawn from the present study:

- The effect of constraint on ductile fracture can be evaluated by local damage model rather than by using conventional fracture mechanics parameters which are inaccurate or even inapplicable in case of large-scale deformation and plastic straining during tearing;
- The small weld metal width in over-matched welded joint has higher resistance to ductile fracture initiation than the wide one and vice versa in under-matched welded joints;
- The most influential constraint on ductile fracture initiation is specimen geometry with loading conditions, while less pronounced effects are obtained for strength mismatching and weld metal width;
- The CGM can predict ductile fracture initiation ($CTOD_i$ value) in welded specimens and effect of constraint level based on the critical void volume fraction, f_c. Ductile fracture initiation parameters, such as $CTOD_i$ can be transferred from one component to another within certain circumstances if their triaxiality conditions are similar.

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УТИЦАЈ ОГРАНИЧЕНОГ ДЕФОРМИСАЊА НА НАСТАНАК ЖИЛАВОГ ЛОМА КОРИШЋЕЊЕМ КОМПЛЕТНОГ ГУРСОНОВОГ МОДЕЛА – НУМЕРИЧКА СИМУЛАЦИЈА

Башир Јунис, Марко Ракин, Бојан Међо, Александар Седмак

Настанак жилавог лома у завареним спојевима нисколегираног челика повишене чврстоће је предвиђен применом микромеханичког комплетног Гурсоновог модела (CGM). Ограничено деформисање око врха прслине (енг. „constraint“) и промена троосности напона у лигаменту су разматрани на епруветама за савијање у три тачке SE(B) и на компактним епруветама за затезање C(T), узимајући у обзир утицај разлике у механичким особинама (енг. „mismatch“) и ширине метала шава. Анализирана је преносивост параметра који одговара настанку прслине, у зависности од троосности напона испред њеног врха и закључено је да се добијене вредности коришћеног параметра могу користити за обе геометрије разматране у раду.