

Material characterisation for ductile fracture by testing of notched tensile specimens

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***ABSTRACT:** Round notched tensile specimens have been used to establish material input data for fracture assessment of high strength 690 MPa structural steel welded joints. Notched tensile testing has been performed both in longitudinal and transversal directions of the heat affected zone and the weld metal. A modified Gurson model in combination with a multi-specimen approach has been applied to retrieve the initial void volume fraction f_0 for the welded joints.*

INTRODUCTION

Correct fracture assessment of welded joints, requires specific material data for the different material zones involved. By traditional cross weld tensile testing methods the overall transversal strength of welded joints can be obtained. Transversal stress strain curves for the heat affected zone (HAZ) and weld metal (WM) can not be obtained by the traditional tensile testing. However, by using round notched tensile specimens, deformation will occur only in the notched area and material data for limited material zones, as the HAZ and WM can be established.

This is an important practical asset for materials characterisation as well as for finite element modelling of fracture. In this paper the study on establishing true stress strain curves and initial void volume fraction, f_0 , for high strength steel weldments (Yield strength of 690 MPa) by using notch tensile testing will be presented.

EXPERIMENTAL STUDY

Materials

The base metal used in the investigation was a 50 mm thick QT steel plate with a prescribed yield strength of minimum 690 MPa. The chemical

composition is given in TABLE 1. Yield and tensile strength in the mid-thickness position were 655 MPa and 745 MPa respectively.

TABLE 1 Chemical composition of the 690 MPa steel

C	Si	Mn	P	S	Al	N	Cu	Mo	Ni	Cr
.16	.430	1.20	.013	.001	.039	.008	.035	.31	.34	.425
V	Nb	Ti	B							
.043	.026	.003	.0002							

The welding procedures were designed to give one yield strength evenmatch and one yield strength overmatch welded joint. The weld configuration was a K- butt joint with a root angle of 45°. The welding position was horizontal. Flux cored arc welding (evenmatch) and submerged arc welding (overmatch) were used. The heat input was in the range of 1.7-2.5kJ/mm. Preheating was minimum 100°C, and interpass temperature was max 200°C. A typical macro section is presented in Figure 1.



Figure 1: Typical macro section of the welded joints

Test specimens

Longitudinal and transversal notch tensile specimens were machined from the top and middle section of HAZ and WM. Specimens were also extracted from the transversal direction of the base metal. The notch centre in the HAZ transversal specimens were localised approximately 1mm from the straight fusion line.

All the specimens had a sample diameter of 6 mm in the notch area. Three different notch geometries were machined: R=3.0 mm, R=1.5 mm and R=0.8 mm. The specimen dimensions are given in Figure 2.

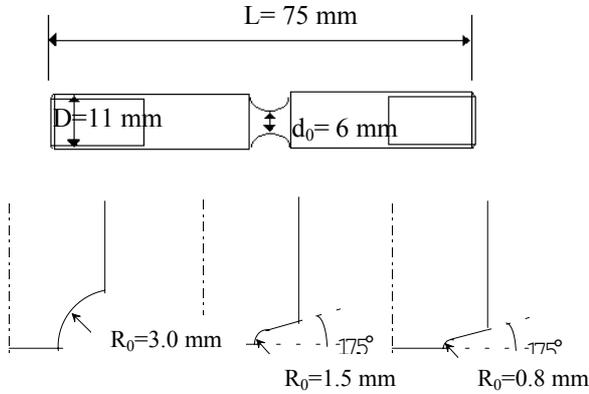


Figure 2: Notch tensile specimen dimensions

Testing

Testing was performed in a universal testing machine in position control with a deformation rate of 0.1 - 0.3 mm/min. A specially constructed 4 point-contact measuring-ring for measurements of the diameter reduction during deformation was used to determine the load versus diameter reduction. The diameter measurements were performed in two directions 90° to each other, taking the mean value as the diameter reduction.

DETERMINATION OF TRUE STRESS STRAIN CURVES

Tensile stress strain curves for the notched specimens, were calculated for all the material zones and directions involved. Tensile stress was taken as P/A , where P is the load and A is the true cross section calculated from the diameter reduction. True strain is calculated as $2\ln(d_0/d)$, where d_0 is the initial diameter and d is the diameter measured during testing.

Typical tensile stress strain curves for weld metal middle section are presented in Figure 3. In the evenmatch weld metal (Figure 3b), somewhat higher stress and lower fracture strain could be observed in the transversal direction. This tendency was not present in the overmatch weld metal (Figure 3a) or in the HAZ.

True stress strain data, as in smooth specimens, were derived by dividing the tensile stress strain data from notched tensile testing by a geometry correction factor G , proposed by Zhang et al [2]. G is a function of the geometry and the hardening exponent (strain at maximum load) by the following expression:

$$G = \left[1.007 + 0.18777 \left(\frac{d_0}{R_0} \right) - 0.01313 \left(\frac{d_0}{R_0} \right)^2 \right] (1.053 - 0.53 \varepsilon_{Pmax}) \quad (1)$$

where d_0/R_0 is the ratio of initial notch diameter and initial notch radius and ε_{Pmax} is the strain at maximum load. G-corrected true stress strain data for the HAZ and WM overmatch is presented in Figure 4.

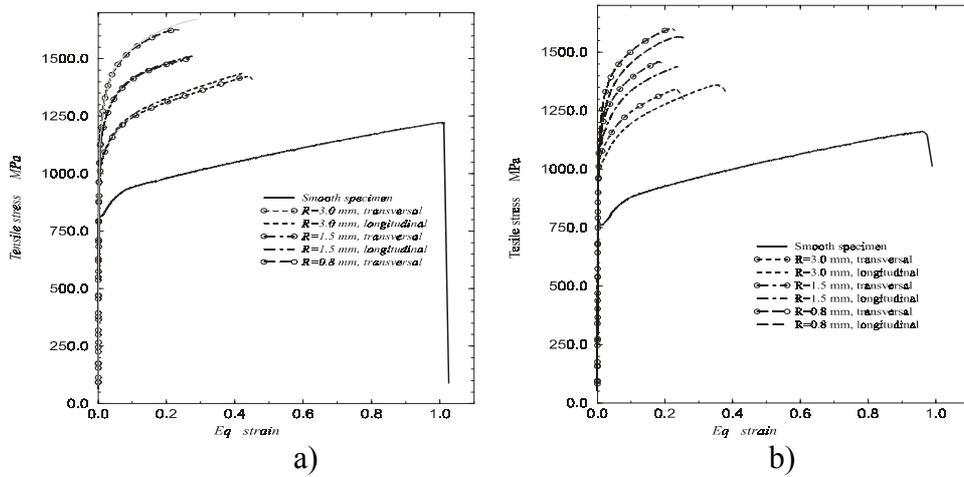


Figure 3: Tensile stress strain curves from notch tensile testing of
a) overmatch WM b) evenmatch WM

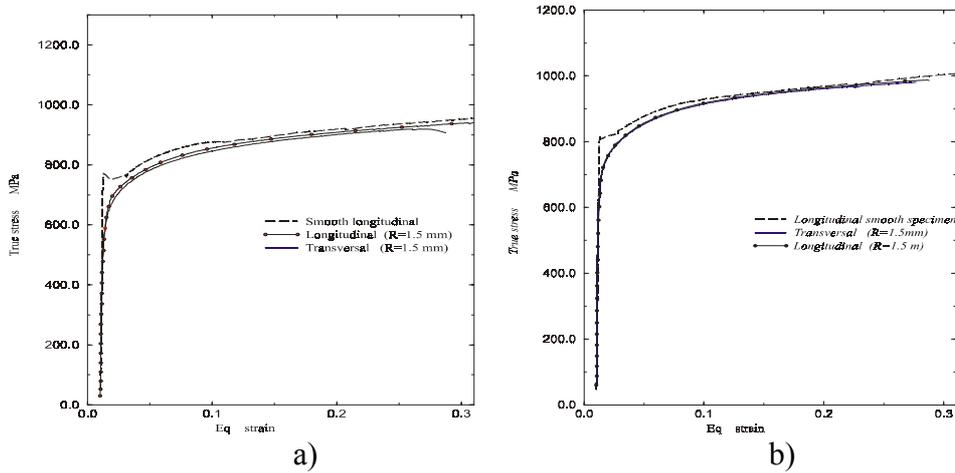


Figure 4: True stress strain curves derived from notch tensile results
a) HAZ b) overmatch WM

The true stress strain curves from the different zones in the welded joint can now be utilised in structural analyses. For the assessment of ductile fracture based on the Gurson model, however, another important input parameter has to be established.

DETERMINATION OF INITIAL VOID VOLUME FRACTION

The modified Gurson model and Gurson parameters

Ductile fracture is a result of micro void nucleation, growth and coalescence. A so-called Complete Gurson Model has been developed by Zhang et al. [1] for modelling of ductile fracture. The model combines the Gurson-Tvergaard model [4] and the void coalescence criterion by Thomason [5].

With the Complete Gurson Model, ductile fracture is only related to the void nucleation parameter, not the critical void volume fraction [1]. The simple cluster nucleation model has been applied in this study. The cluster nucleation model assumes that all the initial voids nucleate at the same time when the plastic strain level, $\bar{\varepsilon}^p$ has reached a certain critical value, $\bar{\varepsilon}_c^p$. This condition can be written as [7]:

$$df_{nucleation} = f_o \delta(\bar{\varepsilon}^p - \bar{\varepsilon}_c^p) \quad (2)$$

f_o is the initial void volume fraction, $\delta(\bar{\varepsilon}^p - \bar{\varepsilon}_c^p)$ is the unitary impulse function (Kronecker function). The position of the impulse is determined by the critical value $\bar{\varepsilon}_c^p$. In this work the commonly used critical value $\bar{\varepsilon}_c^p = 0$, is adopted [7].

FE Analyses and ductility diagrams

FE Analysis was carried out to investigate the stress-strain state and the void coalescence (ductile fracture). The Complete Gurson model was implemented into ABAQUS version 5.8. All the specimens were modelled with axisymmetric quadratic 8 node elements. A reduced integration scheme was adopted.

A single specimen is not able to uniquely determine the f_o , and a ductility diagram which consists of fracture strain at different levels of stress triaxiality has to be used [1]. Ductility diagrams can be created based on the previous notched tensile results.

The fracture strain ε_f was calculated as $2\ln(d_0/d_f)$, where d_0 is the initial diameter and d_f is the diameter at fracture, taken from the load-diameter reduction curves. With a ductility diagram the initial void volume fraction, f_0 , can be generally written as (see Figure 6).

$$f_0 = f_0(\varepsilon_f, T, n) \quad (3)$$

where T is the specimen geometry and n is the materials hardening exponent.

Results

A series finite element analyses for each specimen with varying f_0 has to be carried out to determine the f_0 for each material zone. Figure 5 shows an example for weld metal specimens with a notch radius of 3.0 mm. The strain at initiation of fracture is taken as the fracture strain, ε_f . The location of the fracture initiation is indicated with an arrow in the figure. The ductility diagrams for the base metal, HAZ and WM overmatch are given in Figure 6.

For the base metal, Figure 6a, overall best fit of initial void volume fraction was $f_0=0.0005$ for the top region and $f_0=0.0008 - 0.001$ for the mid-section.

For the HAZ, Figure 6b, $f_0=0.0002-0.0005$ gave the best fit for the top section, while $f_0=0.0005-0.001$ gave the best description of the mid section ductility.

Figure 6c shows that f_0 in the range 0.001 - 0.002 gave the best fit with experimental results for the evenmatch WM. In the overmatch WM joint $f_0 = 0.0005 - 0.001$ best fitted the WM.

The initial void volume fraction is somewhat higher in WM than in the base metal and HAZ. Evenmatch tends to have a higher f_0 than the overmatch WM. There is normally a higher level of inclusions and pores in weld metal than in the steel itself. The results could reflect this. It is however not verified with microstructural investigations. TABLE 2 summarises the best fit initial void volume fraction for all the material zones involved in the investigation.

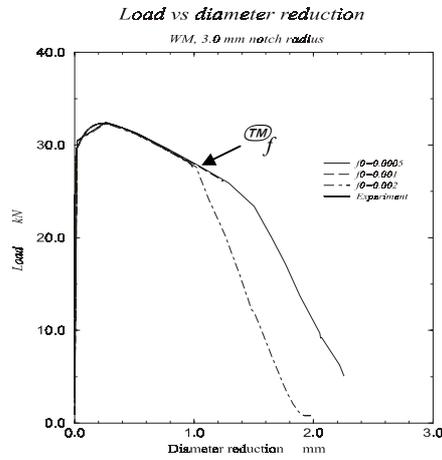


Figure 5: Fitting of initial void volume fraction, f_0

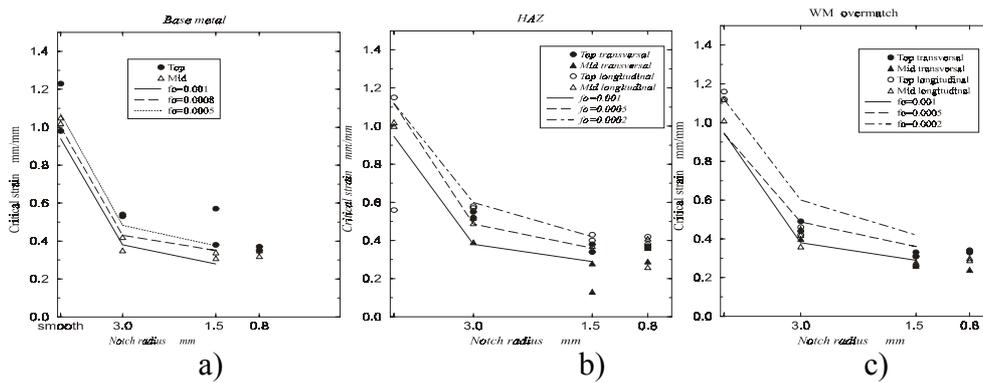


Figure 6: Fitting of initial void volume fraction in ductility diagrams
a) Base metal b) HAZ c) WM overmatch

TABLE 2: Best fit initial void volume fraction, f_0

Welded joint area	Evenmatch		Overmatch		
	f_0		f_0		
	longitudinal	transversal	longitudinal	transversal	
BM	top	-*	0.0005	-*	0.0005
	mid	-*	0.0008 - 0.001	-*	0.0008-0.001
HAZ	top	-*	-*	0.0002-0.0005	0.0002-0.0005
	mid	-*	-*	0.0005-0.001	0.0005-0.001
WM	top	0.002	0.001	0.0005-0.001	0.0005 - 0.001
	mid	0.001	0.002	0.001	0.001

*Not tested

CONCLUSIONS

The notch tensile test in combination with a geometry correction factor has proven a unique possibility of retrieving true stress strain curves for WM and HAZ in the transversal direction of the welded joint.

The presented work have shown that in addition to the true stress strain curves, the initial void volume fraction can also be determined for high strength welded joints by notch tensile testing.

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