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DUCTILE FRACTURE IN HIGH STRENGTH STEEL WELDMENTS

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ABSTRACT

By using the modified Gurson model recently developed at SINTEF, the ductility behavior of high strength steel weldments, including base metal (BM), weld-metal (WM) and heat affected zone (HAZ) in longitudinal and transversal directions has been studied.

A fitting procedure based on smooth and notched cross weld tensile specimens which compares the strain predicted by finite element analyses to the actual strain at coalescence in the experiments, has been applied to determine the initial void nucleation parameter. Two simple models for void nucleation are used in the fitting procedure. Ductility behavior for the weldment has been described as a function of specimen geometry (stress triaxiality) and initial void volume fraction.

Increased stress triaxiality by decreasing notch radius generally results in higher tensile stress and lower ductility. The HAZ ductility level both in longitudinal and transversal direction was slightly lower than for base metal but clearly higher than the WM ductility level. The modified Gurson model, with a void nucleation model describing a sudden initiation of all voids at the early stage of plastic strain (cluster model), gave satisfying description of the ductility behavior for medium sharp notched specimens. The obtained void nucleation parameter f_0 (initial void volume fraction) was 0.0001 for BM and HAZ, and 0.001 for WM.

KEYWORDS

High Strength Steel, weld, ductile fracture, FE-Analysis, Gurson model, notch tensile

INTRODUCTION

Thermo-mechanical production methods have resulted in a new class of high strength construction steels, so called TMCP-steels, low in carbon content with excellent weldability and fracture toughness.

Classical fracture mechanics theory based on brittle fracture will not give a satisfying description of fracture behavior of these steels and welded joints. Failure acceptance criteria based on linear elastic or elastic-plastic relationships are conservative because they fail to include that stress also will be needed for plastic deformation of the material. Hence, there is a need to include a description of ductile fracture in the evaluation of the fracture behavior of TMCP steels.

The Gurson model [8] is a widely known micro-mechanical model for ductile fracture. With modifications by many authors, however, the Gurson model can only simulate void nucleation and growth but not predict ductile fracture. In the modified Gurson model proposed by Z. Zhang [1], ductile fracture is linked to one single void nucleation parameter. Once this void nucleation parameter has been determined, the remaining characteristic length parameter, which describes the inclusion spacing, can be fitted from fracture mechanics tests. The void nucleation parameter and the resulting length parameter are the transferable parameters for ductile fracture.

THE MODIFIED GURSON MODEL

The modified Gurson combines the Gurson-Tvergaard [2] model and the void coalescence criterion by Thomason [3] .

Two simple void nucleation models representing two extreme situations were used. The cluster nucleation model assumes that all the initial voids nucleate suddenly when the plastic strain level, $\bar{\varepsilon}^p$, has reached a certain critical value, $\bar{\varepsilon}_c^p$. This condition can be written as:

$$df_{nucleation} = f_o \delta(\bar{\varepsilon}^p - \bar{\varepsilon}_c^p) d\bar{\varepsilon}^p \qquad (1)$$

f_o is the initial void volume fraction that has to be fitted. $\delta(\bar{\varepsilon}^p - \bar{\varepsilon}_c^p)$ is the unitary impulse function (Kronecker function) and the position of the impulse are determined by the critical value $\bar{\varepsilon}_c^p$. In this work the commonly used critical value $\bar{\varepsilon}_c^p = 0$, is adopted.

The second nucleation model proposes that voids nucleate continuously during plastic loading. The nucleation rate is constant. Such simple continuous nucleation model can be written as:

$$df_{nucleation} = A d\bar{\varepsilon}^p \qquad (2)$$

The constant A is the damage parameter to be fitted. Equations 1 and 2 have greatly simplified the nucleation modelling and reduced the number of the unknowns of the nucleation process into one.

TENSILE TESTING

The material investigated was a welded joint in a 70 mm TMCP steel plate, welded by double-sided SAW. Yield strength level was 500 MPa and the main alloying elements were C (0.07%), Mn (1.5%), Ni (0.43%), Al (0.035%) and Nb (0.020%). Microstructure of the steel was polygonal ferrite and bainite. Areas subjected to investigation were the base metal (BM) the heat-affected zone (HAZ) and the weld metal (WM). Ductile crack initiation behavior was determined by using the multi specimen approach, including both smooth and notched round bar tensile specimens. HAZ and WM were tested in longitudinal and transversal direction, base material in longitudinal direction only.

Both smooth and notched specimens had a cross sectional diameter of 6.0 mm. Four different notch geometries with notch radiuses of 3.0 mm, 2.0 mm, 1.0 mm and 0.4 mm respectively, were prepared to represent different levels of stress triaxiality.

The tensile specimens were extracted from four different locations with respect to the plate surface as shown in Figure 1. Notch bottom of the HAZ transversal specimens was located 1.0 mm outside the horizontal fusion line.

Tensile testing was conducted in a 250 kN INSTRON 1126 testing machine. The crosshead speed during the tests was 0.01 mm/s for the smooth specimens, and 0.005 mm/s for the notched specimens. Accurate measurement of diameter reduction during the tensile test is essential for the establishment of the Bridgman corrected true stress-strain curve.

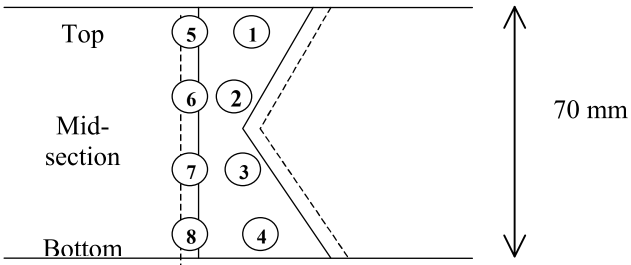


Figure 1: Location of longitudinal tensile specimens in WM and HAZ

This was performed by direct measurements of the diameter reduction during testing. The measurements were performed in two orthogonal directions normal to the tensile axis using 4 displacement gauges in a special designed fixture.

FINITE ELEMENT ANALYSES

FE Analyses were carried out to investigate the stress-strain state and the void coalescence (ductile fracture). The modified Gurson model were implemented into the FE Program ABAQUS version 5.8. All the specimens were modeled with axisymmetric quadratic 8 node elements. A reduced integration scheme was adopted. Due to symmetry conditions, only one quarter of the specimens was modeled. The nodes at the top end of the model were used to prescribe a monotonic vertical displacement to simulate the uniaxial loading situation.

The material models were defined by representative Bridgeman corrected true stress strain data from the smooth specimens, with modulus of elasticity E=210000 MPa and Poisson's ratio ν=0.3. Since no Bridgeman corrected stress strain curve could be obtained for the transversal direction the transversal fitting procedure was carried out using stress-strain curves from the longitudinal direction.

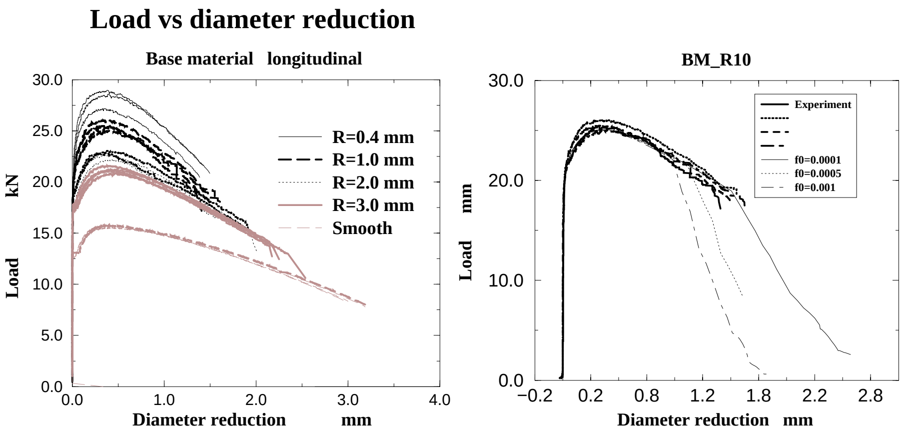
RESULTS

Base material

Figure 2a shows and overview of load vs. diameter reduction for all base material specimens. Figure 2b shows simulated curves for notch radius R = 1.0 mm fitted by different values of the Gurson parameter f_0. The results clearly show that increased stress triaxiality represented by decreasing notch radius causes a rise in the load level and a lowering of the diameter reduction at fracture. The fitted curves for R=1.0 mm agrees well with the experiment for f_0 = 0.0001.

After performing the fitting procedure for all geometries, the results were evaluated in ductility diagrams, comparing the measured and simulated strain at the beginning of final fracture, ε_c (Figure 3) In the experiments the critical strain was taken as the strain at maximum true stress. In the FE-analysis ε_c was represented by the strain at the initiation of failure, represented by a sudden load drop. Critical strain is plotted as a function of notch radius. Black points represent experimental values. Simulated results are represented by curves.

The best fit for the base metal was obtained for the cluster nucleation model with f_0 = 0.0001. The continuos model with A= 0.0005 also fitted the experimental results reasonably well, except for the smooth and sharpest notched specimens. It can be noticed that the model predicts higher ductility for the R0.4 than for the R1.0 specimens. The experimental results, however, showed relatively similar ductility values for these two geometries.



a b

Figure 2: Load vs diameter reduction for base metal a) overview of all results b) f_0 fitted curves for R=1.0mm

The level of non-metallic inclusions in the base metal has been evaluated by Olden [5]. By counting of particles larger than 1 μm a volume fraction of 0.00014 was found. If one assume that voids primarily nucleate from these inclusions, the obtained f_0 value of 0.0001 matches the inclusion level very well.

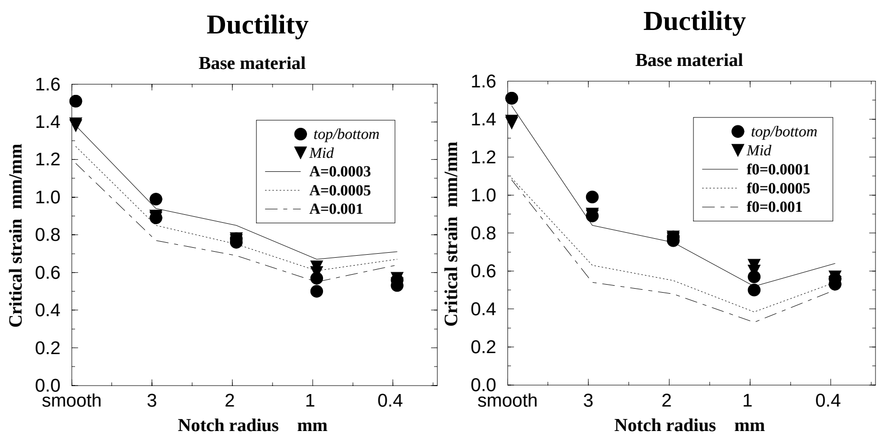


Figure 3: Ductility diagrams for the base metal. Continuos nucleation model (left) and cluster nucleation model (right)

Weld Metal

Weld metal was tested in longitudinal and transversal direction. In longitudinal direction the specimen geometries were smooth and notched with R=3.0 mm, R=1.0 mm and R=0.4 mm. In the transversal direction smooth specimens were omitted and the notch geometry R=2.0 mm was included in the test program.

Weld metal results were more scattered than the base metal results. The results also showed more scatter in the transversal direction than in the longitudinal direction. The transversal mid-section specimens had the overall lowest ductility, with a critical strain of about 0.2 for all notched geometries (Figure 4). This may indicate that other factors than the stress triaxiality level have influenced the ductility. Investigations of the welded joint [5] have revealed coarse dendrite austenite grain boundaries in weld metal. Measured hardness was also somewhat higher in the mid-section (230 - 250 HV) than in the “top” and “bottom”-region (200 - 220 HV). Accordingly there is a possibility that the brittle nature of the microstructure has influenced the results more than the stress conditions.

The tensile testing produced a large scatter in ductility results. The mid section R0.4 longitudinal specimens (all weld) achieved clearly lower ductility values than the R1.0 specimens, while the top/bottom specimens showed the same or slightly higher values.

In the longitudinal direction, the best fit was achieved for the cluster nucleation model with f_0=0.001 (Figure 4 left).

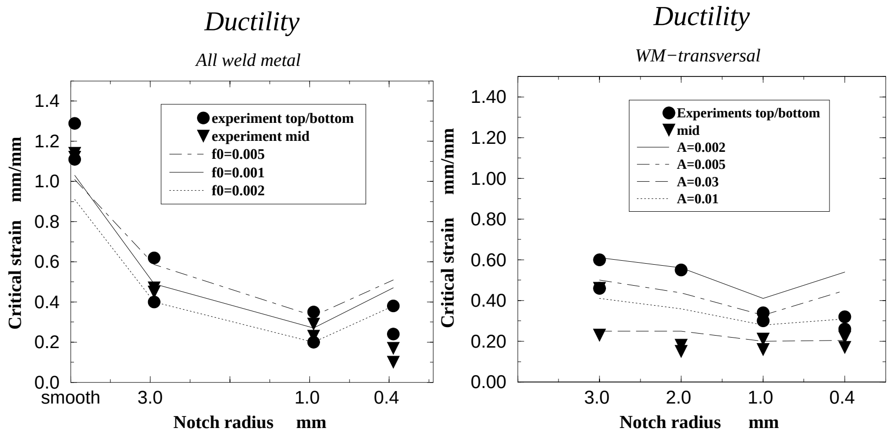


Figure 4: Ductility diagrams for WM. Longitudinal direction and cluster model (left), transversal direction and continuos model (right).

Both nucleation models, however, gave poor fit for the smooth and R=0.4 mm notched specimens with respect to ductility.

In the transversal direction, good fit for the mid-section specimens was achieved for the continuos model with A = 0.03 (Figure 4 right), and for the cluster model with f_0 = 0.005. Volume fraction of non-metallic inclusions in weld metal was measured in the range of 0.002 - 0.004 [5], which is approximately in the same range as the void volume fraction established by the model. Regarding to these results the cluster model with f_0= 0.001 gives a good description of longitudinal weld metal. In the transversal direction f_0=0.005 gives better representation of the ductility behavior.

The obtained values for f_0 in BM and WM agrees well with the findings in a previous SINTEF investigation of a welded joint in X-65 pipeline steel [6].

Heat affected zone

As for weld metal, there is a tendency of higher load levels and lower ductility for the mid section specimens (Figure 5). This tendency is slightly more pronounced in the transversal than in the longitudinal direction. However, comparing the tensile testing results of the longitudinal and transversal direction, the overall load and ductility level is quite similar.

Higher hardness values were found in the mid-section HAZ than in the top and bottom area. Higher hardness and lower ductility in the mid-section is proposed related to the welding procedure. Welding of the first passes (on both sides) were performed with lower heat input (1.5 MJ/m) compared to the rest of the weld (3.0 MJ/m). This will give shorter $\Delta t_{8/5}$ in the mid-section HAZ, and influence hardness and tensile properties [5][7].

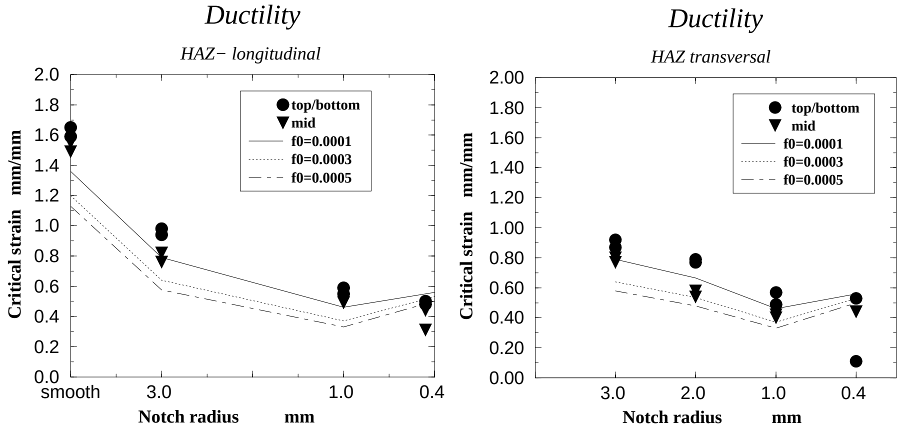


Figure 5: Ductility diagrams for HAZ. Longitudinal direction and cluster model (left), transversal direction and cluster model (right).

The cluster model with f_0 =0.0001 gives the best fit both in longitudinal and in transversal direction, see Figure 5. The level of non-metallic inclusions is the same in base metal and HAZ. Consequently the obtained level of f_0 could be expected. As for base metal and WM the model tends to overestimate the ductility of the R0.4 specimens and to underestimate the ductility of the smooth specimens.

EVALUATION OF THE MODEL

The modified Gurson model predicts higher ductility for the sharpest notched (R=0.4 mm) specimens than the R=1.0 mm specimens. This is based on a shift in damage process from stress to strain controlled initiation of fracture [6]. Strain controlled plastic initiation allows more plastic deformation and the ductility level will rise. The experiments show, however, that the model overestimates the critical deformation in the sharpest notched specimens.

When evaluating the model one must bear in mind that several simplifications are made. The model is based on the assumption that the material behaves like a continuum, and that the plastic strain happens in a distributed manner. If the plastic strain varies locally caused by defects or weak zones in the matrix, the critical plastic strain will be lower. The ductility level of the R=0.4 mm tensile specimens may well reflect the effect of non-homogeneity in the matrix. It can be noted that the ductility level of the R0.4 specimens in weld metal, which has the highest level of non-metallic inclusions, varies the most.

Both the cluster and the continuos void nucleation models are simplifications of the nucleation process. Perhaps does a more detailed void nucleation model better describe the process of void nucleation.

The material, as described by the Bridgeman corrected plastic stress strain-curve for smooth specimens, is supposed to represent all geometries. This may not be the best representation of the material behavior for the sharpest notched specimens. One can argue also that the longitudinal stress-strain curves do not represent the correct material behavior in the transversal direction. As presented the model seems well suited to describe the ductility behavior of medium sharp notched tensile specimens in the range $\frac{D_0(\text{Initial diameter})}{R(\text{notch radius})} = 2 - 6$.

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