Numerical simulation and experimental investigation of the damage behavior on electron beam welded joints

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Abstract

Experimental and numerical investigations of crack propagation on S355NL steel electron beam welded joints are presented. Mechanical properties are obtained from tensile test results of flat specimens extracted from the base material (BM), the fusion zone (FZ) and heat affected zone (HAZ), respectively. Based on metallographic investigations, numerical calibration of Rousselier parameters are performed on notched round specimens. The same parameters are used to predict the ductile fracture of compact tension (C(T)) specimens with initial crack located at different regions. Numerical results are compared with the experiments in terms of force vs. Crack Opening Displacement (COD) as well as fracture resistance (J_R) curves.

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1. Introduction

Nowadays advanced welding techniques, such as electron beam welding (EBW) are used widely in transportation and aircraft industries. As the properties of welded joints influence the mechanical behaviour of welded constructions, attention has been focused on the fracture behaviour of welded joints in a numerical way.

In ductile material, failure can be described by void initiation, growth and coalescence. Similar to the GTN model [1-3], based on a thermodynamical framework, a model was developed by Rousselier which involves less model parameters [4, 5]. After solving fracture problems of different homogeneous
materials [6, 7], scientists are trying to investigate the fracture behaviour of laser-hybrid welds with the GTN model [8-11]. Recent works have confirmed the GTN model can predict the crack propagation of a welded joint well; however, whether the Rousselier model can be used to solve the problem of an EBW joint is unknown. In this article, the Rousselier model will be used to study the fracture behaviour of EBW joints.

2. Material properties and experiments

Low-alloyed structural steel S355NL is chosen as BM to make welded joints. After the electron beam welding process, a butt joint is obtained from two S355NL plates with the thickness of 60 mm. The chemical components of S355NL are shown in Table 1, which is obtained from spectrometric analysis.

In order to identify the different weld regions, especially the fusion zone (FZ) and the heat affected zone (HAZ), the hardness is measured across the weld. From the hardness test results, the dimensions of FZ and HAZ are found to be 2.8 mm and 3.1 mm, respectively. Local mechanical properties of different weld regions of S355 EBW joints are obtained from flat specimens along the weld line. These local stress strain curves are used as finite element model input data. Table 2 shows the mechanical properties of the welded joints containing yield stress \( R_e \), tensile strength \( R_m \), uniform strain \( A_g \) and strain at rupture \( A \).

Table 1: Chemical composition of the steel S355NL, mass contents in %

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Al</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355NL</td>
<td>0.198</td>
<td>0.260</td>
<td>1.386</td>
<td>0.026</td>
<td>0.013</td>
<td>0.020</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>0.013</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Table 2: Mechanical properties of different weld regions of S355NL EBW joint

<table>
<thead>
<tr>
<th></th>
<th>( R_e^{BM} ) (MPa)</th>
<th>( R_e^{FZ} ) (MPa)</th>
<th>( R_m^{BM} ) (MPa)</th>
<th>( R_m^{FZ} ) (MPa)</th>
<th>( A_g^{BM} )</th>
<th>( A_g^{FZ} )</th>
<th>( A_e^{BM} )</th>
<th>( A_e^{FZ} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>348</td>
<td>513</td>
<td>533</td>
<td>687</td>
<td>0.151</td>
<td>0.037</td>
<td>0.295</td>
<td>0.052</td>
</tr>
</tbody>
</table>

After surface etching, the microstructures of different weld regions are shown in Fig. 1(a)-(c). As shown in Fig. 1(a), the BM shows typical dual phase structures, which is comprised of Ferrite and Perlite. The microstructure of the HAZ around the fusion line can be found in Fig. 1(b), which is a transitional region between the BM and the FZ. In Fig. 1(c), acicular martensite structures can be found in the FZ. This can explain the brittle behaviour of the fusion zone.

The fracture surfaces of notched round specimens extracted from the BM show typical honeycomb structures as observed in Fig. 2(a)-(b). The fracture surfaces show typical ductile fracture characteristics, large voids are next to smaller voids [8]. This indicates that the fracture of the BM is controlled by void nucleation, growth and void coalescence during deformation.

Fig. 1: Microstructures of different weld regions of an S355 EBW joint: (a) base material, (b) heat affected zone, (c) fusion zone.
In this work, fracture toughness tests are performed on C(T) specimens with different configuration, i.e. the initial crack is created in the BM, in the middle of the FZ and at the interface between the FZ and the HAZ, separately. Standard compact tension specimens (C(T)25) with 20% side grooves are chosen for the test. During testing, the load is controlled by quasi-static displacement. After the C(T) test, the experimental results are shown in terms of force vs. Crack Opening Displacement (COD) as well as fracture resistance \( J_R \) curves. As FZ shows higher tensile strength compare to that of BM, see Fig. 3, a C(T) specimen with the crack in the FZ shows higher fracture toughness compare to BM as shown in Fig. 4. For a C(T) specimen with the crack in the FZ, the specimen suddenly ruptures, showing typical brittle fracture behaviour. This coincides with the material character of the FZ. In this paper, the Rousselier model has been used to study the ductile crack growth of the BM and HAZ structures.

3. Finite simulations and results

In the frame of continuum damage mechanics a model for porous metal plasticity is presented by G. Rousselier [4, 5]. In the Rousselier model, damage is defined by the variation of the void volume fraction. Rousselier suggested in the case of a damaged material that the yield surface had to be corrected as follows:
\[
\Phi = \frac{\sigma_{eq}}{1-f} + Df\sigma_K \exp\left(\frac{\sigma_m}{\sigma_K(1-f)}\right) - R(p) = 0
\]  
(1)

where \( \sigma_{eq} \) is the von Mises equivalent stress, \( \sigma_m \) is the hydrostatic stress, \( f \) is the void volume fraction (initial value \( f_0 \)), \( \sigma_K \) and \( D \) are material constants, and \( R(p) \) is the true stress-true plastic strain curve of the material.

The initial void volume fraction, \( f_0 \), depends on the volume fraction of non-metallic inclusions, like sulphides and oxides, as explained, e.g., by Schmauder [7]. The actual void volume fraction \( f \) can be calculated from current stress according to equation 1. When the critical void volume fraction is reached, the element stiffness will be set to zero, as suggested by Seidenfuss [6]. For ductile fracture, within the framework of damage models, it is assumed that a crack propagates from void to void. This can be simulated by the finite element model that a crack propagates from integration point to integration point. As voids originate mainly from non-metallic inclusions, if square finite elements with 4 integration points are used for the calculation, the main distance between voids \( l_c \) is equal to half of the element size. In this work, the Rousselier parameters can be fixed based on combined experimental investigations and numerical calibration about the notched round specimens. The same Rousselier parameters are used to predict the crack propagation of C(T) specimens. All the simulation works are performed on ABAQUS platform with the Rousselier model as a user subroutine (UMAT) [12].

From these explanations, the initial void volume fraction \( f_0 \) and average distance between voids \( l_c \) are the Rousselier model parameters to be fixed. These Rousselier parameters can be obtained from the optical microscope pictures. From the optical microscope pictures of BM and HAZ, not shown at here, the voids are not average distributed but localize at some regions. Before adopted in the Rousselier model directly, these experimental values should be calibrated numerically. For the BM, numerical calibrations are performed based on force vs. diametral reduction curves of notched round specimen. Typical \( l_c \) values (\( l_c=0.05 \) mm, \( l_c=0.1 \) mm) which influence the slope of force vs. diameter reduction curves after the fracture point are used for the calibration of \( f_0 \), see Schmauder [7]. For notched round specimens with 4mm notch radius, good agreement can be obtained when \( l_c=0.05 \) mm and \( f_0=0.001 \). This calibrated \( f_0 \) value is very close to the experimental quantitative value \( (f_0=0.0009) \). In Fig. 5(a), for C(T) testing, the conventional elastic plastic material behaviour provides a good agreement to the experiments until the crack initiates. However, as no damage is considered during the deformation, the elastic plastic behaviour overestimates the force after the crack appears. In consideration of damage influence, the Rousselier model can reliably predict F-COD curves of C(T) specimens with the initial crack located in the BM. In Fig. 5(b), the Rousselier model can also predict the crack propagation of C(T) specimen on the BM well.

![Fig. 5: Comparison of experimental and numerical (a) force vs. crack opening displacement (COD) curves, and (b) fracture resistance curves for C(T) specimen with initial crack locates in the BM.](image-url)
For the C(T) specimen with the initial crack located at the interface between the FZ and the HAZ, the elastic plastic material behaviour is also in good agreement until the crack initiates. As the result of metallographic investigation on HAZ is very similar to that of BM, the same \( l_c \) value is used for the simulation. From the experimental investigations, the crack only propagates in the HAZ and no crack was observed in the FZ and in the BM. In the finite element simulations, the mechanical properties of FZ and BM are defined as non-damaging elastic plastic. The HAZ is divided into three tiny regions which can reflect different material behaviour. After the calculation, good agreement can be found when the initial void volume fraction \( f_0 \) equals to 0.0005, which is smaller than that of the BM, as shown in Fig. 6.

![Fig. 6: Comparison of experimental and numerical force vs. crack opening displacement (COD) curves for C(T) specimen with initial crack located at the interface between the FZ and HAZ.](image)

4. Discussion and conclusions

Experimental and numerical investigations on the fracture behaviour of S355NL electron beam welded joints have been presented. Fracture toughness tests are performed on different C(T) specimens, i.e., the initial crack is located in the BM, in the middle of the FZ and at the interface between the FZ and the HAZ. Microstructures of different weld regions are shown. C(T) specimens with an initial crack locates in the FZ show brittle behaviour, which results from the character of martensite microstructure. Fracture surfaces of BM confirm that void initiation, growth and coalescence are the main reasons for ductile fracture. Ductile fracture behaviour is studied with the Rousselier model.

Before using the Rousselier model to predict the ductile fracture of C(T) specimens, the Rousselier parameters are fixed. Metallographic investigations are performed on the BM and HAZ in order to identify the respective void volume fraction \( f_0 \) and the average void distance \( l_c \). As the voids are clustered in some regions, numerical calibration is performed on notched round specimens extracted from the BM. The same parameters are used to predict crack propagation of C(T) specimens gotten from the BM. Good agreement can be obtained in the form of force vs. crack opening displacement and fracture resistance \( J_R \) curves. This confirms the Rousselier model can predict the crack propagation of the homogeneous base material well.

For C(T) specimens with the initial crack in the HAZ, because of the similar distribution of non-metallic inclusions in HAZ compared to that of BM, the same \( l_c \) value is applied for the calculation. Local mechanical properties obtained from flat specimens extracted from these regions are used as model input. The HAZ is one transitional zone; there is big scatter of material behaviour within this region, see Fig. 3. For this reason, the HAZ is divided into three tiny regions which can reflect different material behaviour. Good agreement can also be achieved when \( f_0=0.0005 \), which is smaller than that of BM, leading to later crack propagation of the HAZ. All in all, good simulation results on C(T) specimens with the initial crack
located in the BM and HAZ confirm that the Rousselier model can predict the crack propagation of homogenous BM and inhomogeneous welded joints well.

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References