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Modelling the effect of HAZ undermatching on the crack-tip stress distribution in idealized welds

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Abstract

In order to study the influence of the heat-affected zone softening on the fracture behaviour of welds with cracks in the weld metal centre line, a large variety of weld geometries and undermatch conditions of the heat affected zone mechanical properties, relative to the weld metal and base material, were addressed in this study. With this aim, the opening stress distribution in notched welded specimens was analysed using the numerical simulation of the three-point bending test. The numerical results show a reduction in the stress levels ahead of the crack tip for welded specimens with severe heat-affected zone undermatch. The stress distribution is strongly influenced by the crack position relative to the weld material/heat-affected zone interface, independently of heat-affected zone width.

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1. Introduction

Most of the published numerical studies on the fracture behaviour of welds with cracks located in the weld metal (WM) have neglected the presence of the heat-affected zone (HAZ), thus representing the welds as bi-material systems constituted exclusively by the WM and base material (BM). However, it is well known that the thermal cycle associated with the fusion welding processes can cause strong changes of the BM characteristics in the HAZ [1–3]. This is the case in

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high-strength steels for which high-energy inputs and slow cooling rates can cause a considerable loss in the yield strength of the base plate [4–7].

To the author's knowledge, no previous attempt has been made to conduct a parametric study on the fracture behaviour of this type of welds considering HAZ undermatched conditions for several weld dimensions. A few numerical studies were published regarding the specific situation of welds with cracks in the weld material centre line that focussed on very specific situations, in which the HAZ is represented as a very narrow portion of material with overmatched mechanical properties relative to both base and weld material [8–10].

This text presents a numerical study concerning the influence of HAZ softening on the crack-tip stress distribution in welds with cracks in the WM centreline. This study was performed through the numerical simulation of three-point bending tests (TPB), using finite element models of samples with various undermatch conditions and weld dimensions. The numerical simulations were performed with the code EPIM3D, which is a quasi-static finite element code developed to simulate problems that involve large elastoplastic deformations and rotations [11].

2. Material modelling and numerical procedures

2.1. Material properties

The different weld zones (BM, HAZ and WM) are assumed to have isotropic elastoplastic behaviour with isotropic work-hardening described by the Swift power equation:

$$Y(\bar{\epsilon}^p) = C(\epsilon_0 + \bar{\epsilon}^p)^n. \quad (1)$$

In this equation, $\bar{\epsilon}^p$ is the equivalent plastic strain and n , C and ϵ_0 are material constants, with n being the hardening coefficient.¹ In order to represent the HAZ softening, and to cover a large range of undermatch conditions of this zone relative to the adjacent materials (WM and BM), the numerical simulations were performed using various hypothetical values for the HAZ yield stress ($Y_0 = 400, 500$ and 600 MPa) and for the HAZ hardening coefficient ($n = 0.08$ and 0.16). For the WM and BM, the same high-strength mechanical properties were used, representing an evenmatch weld with 700 MPa yield stress and hardening coefficient, $n = 0.08$. These values are common in welds produced with increasing heat-input in high-strength thermomechanical control processed steels and in quenched and tempered steel welds. Fig. 1 presents the stress–strain curves plotted according to Eq. (1), for the various materials studied. The curves for each material are plotted in the figure up to the stress (Y_{TS}) corresponding to the maximum load in tension; from Eq. (1), $Y_{TS} = Cn^n$. Similar elastic properties were considered for all the materials ($E = 200$ GPa and $\nu = 0.33$). The TPB test of a homogeneous sample with the same mechanical properties of the adjacent materials was also simulated.

2.2. Finite element modelling

One of the finite element meshes used in this study is shown in Fig. 2. In this mesh different material regions and the crack depth (a) are clearly shown. The boundary conditions for the

¹The HAZ is represented as a homogeneous material with average mechanical properties.

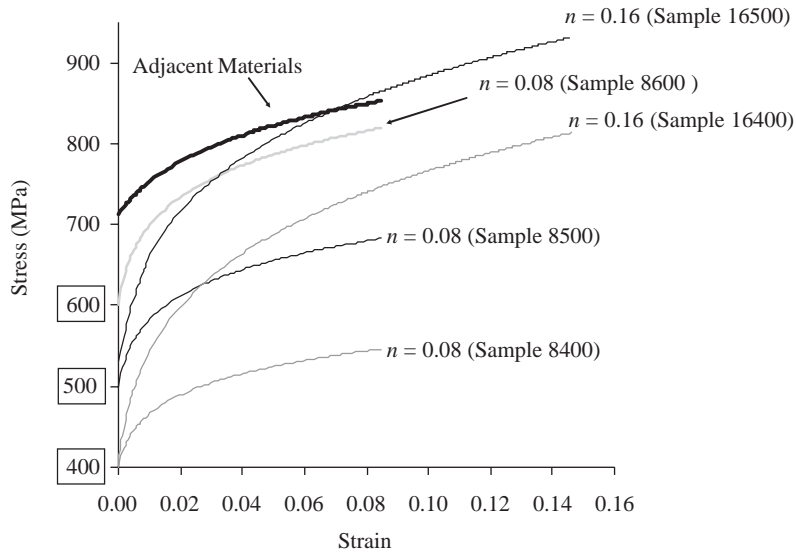


Fig. 1. Stress–strain curves for the various materials considered in the study, plotted according to the Swift equation (1). $\epsilon_0 = 0.0018$, $C = (Y_0/\epsilon_0)^{1/n}$ and $Y_{TS} = Cn^n$.

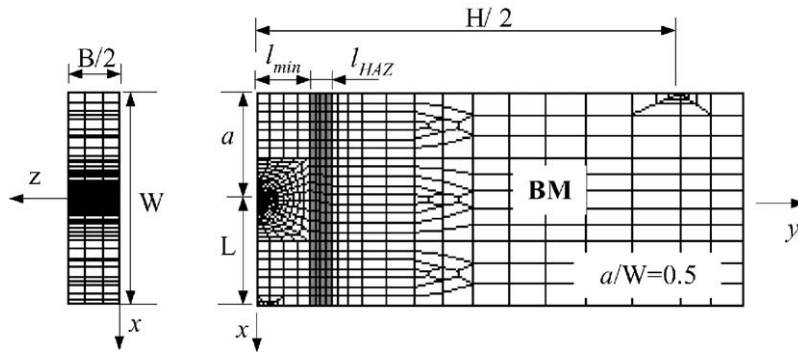


Fig. 2. Finite element mesh used in the numerical simulation of the three-point bend tests of deep crack specimens (20-node elements were used). a represents the crack depth, L the ligament length, $W = 20$ mm, $H = 80$ mm and $B = 20$ mm.

numerical simulation of the TPB test were settled assuming the existence of geometrical and material symmetry relative to the axes Oy and Oz , simulating only $\frac{1}{4}$ of the sample (symmetry conditions in the uncracked ($y = 0, 0 \leq x \leq L$) and $z = 0$ planes). The movement in the z direction of the nodes located in the plane $z = B/2$ was also restricted. This requirement insures a plane strain state at the crack tip, simulating extremely severe conditions for fracture [12].

In order to evaluate the influence of the WM and HAZ size on the fracture behaviour of the welds, various HAZ and WM widths were considered in the numerical simulations. In Fig. 2, l_{haz} is the HAZ width and $l_{min} = l_{wm}/2$ (l_{wm} – weld metal width) represents the distance from the crack tip to the WM/HAZ interface. The following was assumed in this study: $l_{haz} = 2$ and 5 mm

and $l_{wm} = 6, 8$ and 10 mm ($l_{min} = 3, 4$ and 5 mm). These different samples are identified using simple codes of the form HAZXWMY, where X and Y represent the HAZ and WM widths, respectively. For example, a sample for which $l_{haz} = 2$ mm and $l_{wm} = 10$ mm is identified with the code HAZ2WM10.

3. Results and discussion

3.1. Stress distributions in specimens with different HAZ and WM widths

In this analysis, the near-tip stress, normal to the crack line (σ_{yy}), was plotted against position x of the finite element nodes lying along the crack line in front of the tip ($\theta = 0^\circ$) in the undeformed configuration (see Fig. 3a). Since the TPB test was simulated assuming plane strain conditions, the stress distributions were constant along the crack front, and the results presented in the graphs correspond to one of the symmetry planes of the samples ($z = 0$). The stress results were normalised in relation to the yield stress of the weld material (Y_0^{wm}) and plotted for a load level corresponding to an imposed displacement $\Delta = 0.6$ mm (see Fig. 3b).

The opening stress σ_{yy} distribution ahead of the crack is shown for the various types of samples in Fig. 4a, b and c, and for the weld geometries corresponding to $l_{min} = 3, 4$ and 5 mm ($l_{wm} = 6, 8$ and 10 mm), respectively. In each graph, the results correspond to the samples with the most severe undermatch conditions in the HAZ ($Y_0^{haz} = 400$ MPa and $n^{haz} = 0.08$, see Fig. 1) and to the WM homogeneous sample.

On analysing this figure, it is possible to observe that a maximum value in the opening stress exists some distance ahead of the crack tip in all the plots (graphs a, b and c). This maximum is a consequence of crack-tip blunting, which causes a local reduction in stress triaxiality, promoting a decrease in σ_{yy} , very close to the crack tip [13–15].

On comparing the three graphs it is possible to conclude that the maximum stress and the general stress distributions ahead of the crack are similar for the specimens with different HAZ widths (HAZ2 and HAZ5). Upon comparing the results according to the crack position (l_{min}), it is possible to conclude that the maximum stresses are lower for the weld geometries corresponding to $l_{min} = 3$ mm (WM6 samples). Because of the fact that stress values are smaller for the welded samples than in the homogeneous one, critical conditions for the occurrence of fracture are

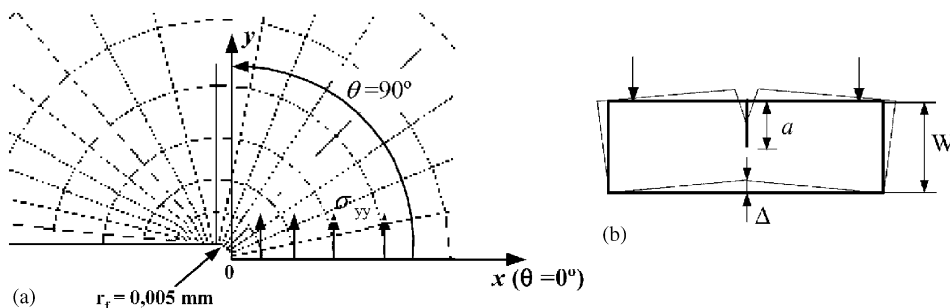


Fig. 3. (a) Crack tip mesh configuration. (b) Sketch of the sample.

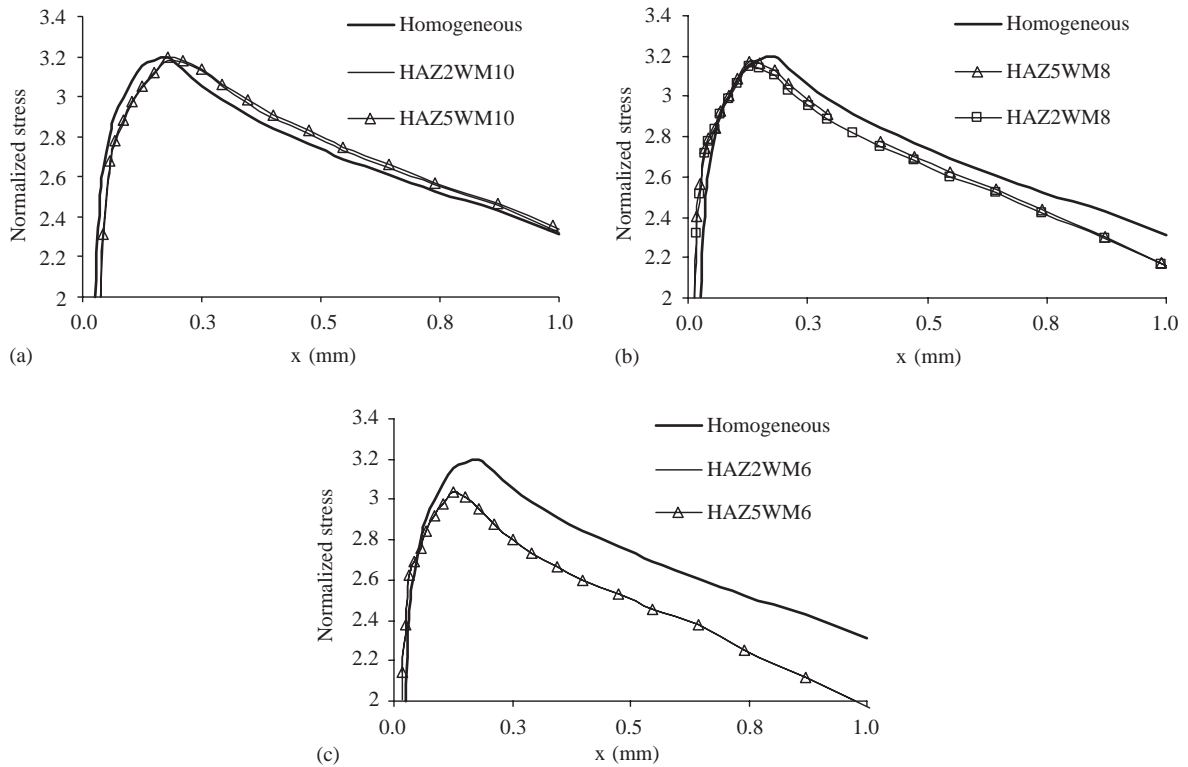


Fig. 4. Normal stress distribution (σ_{yy}) ahead of the crack-tip. (a) $l_{min} = 5$ mm, (b) $l_{min} = 4$ mm and (c) $l_{min} = 3$ mm. HAZ material ($\sigma_0^{haz} = 400$ MPa, $n^{haz} = 0.08$). Normal stress axis is normalized by σ_0^{adj} .

expected to be reached later in these particular welds. For $l_{min} = 5$ mm (WM10 samples) the stress levels were similar to the homogeneous sample, which indicates that there is no influence of the soft zone on the fracture behaviour of the weld.

All the results presented suggest that the influence of the HAZ softening on the fracture behaviour of the welds is essentially conditioned by the distance from the crack tip to the soft zone, independent of the width of this zone. In order to verify if the fracture behaviour is effectively independent from the soft zone width, new simulations were performed using two new types of meshes. The new meshes represent weld samples with different WM widths ($l_{wm} = 6$ and 10 mm) and very large HAZ widths (WM/HAZ bi-material system). These samples are identified as WM6HAZ ($l_{min} = 3$ mm) and WM10HAZ ($l_{min} = 5$ mm) according to their WM width. The results corresponding to these new simulations are presented in Fig. 5, together with the results of the WM homogeneous sample and the weld samples HAZ2WM6 ($l_{min} = 3$ mm and $l_{haz} = 2$ mm) and HAZ2WM10 ($l_{min} = 5$ mm and $l_{haz} = 2$ mm). The graph in the figure represents the stress distributions ahead of the crack tip when $\Delta = 0.6$ mm.

The results in Fig. 5 show that when the distance from the crack tip to the soft zone is large ($l_{min} = 5$ mm), the influence of the HAZ on the fracture behaviour of the weld vanishes, and the stress levels are similar to the homogeneous sample, even for the sample with a very large HAZ width (WM10HAZ). In comparing the results of samples WM6HAZ and HAZ2WM6

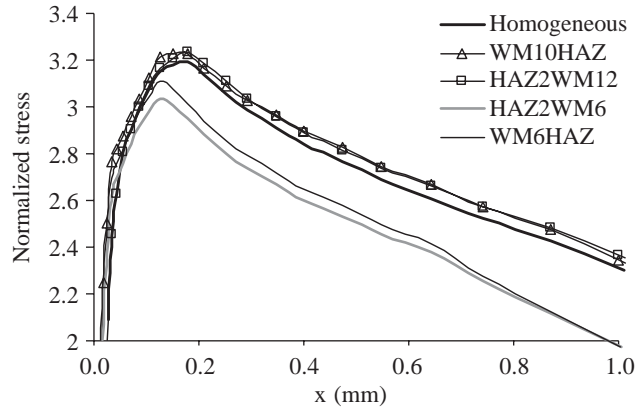


Fig. 5. Normal stress distributions ahead of the crack-tip. These results correspond to the homogeneous sample and WM10HAZ ($l_{min} = 5$ mm, very large HAZ), WM6HAZ ($l_{min} = 3$ mm, very large HAZ), HAZ2WM10 ($l_{min} = 5$ mm, $l_{haz} = 2$ mm), HAZ2WM6 ($l_{min} = 3$ mm, $l_{haz} = 2$ mm). HAZ material: $\sigma_0^{haz} = 400$ MPa, $n^{haz} = 0.08$.

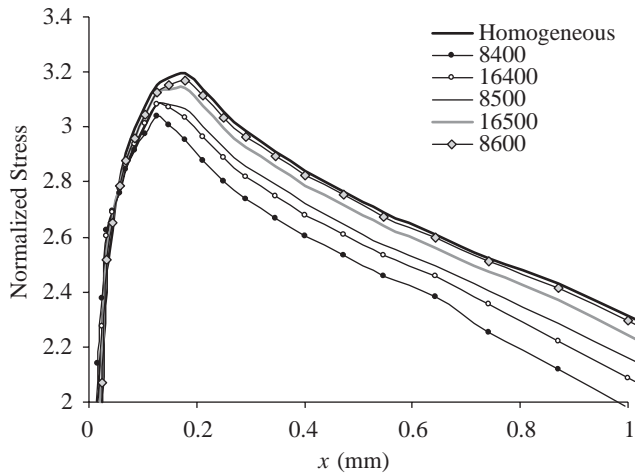


Fig. 6. Normal stress distributions ahead of the crack-tip. Sample HAZWM6. Several undermatch conditions of the HAZ.

(same l_{min} and different l_{haz}) it is also possible to confirm that the influence of the soft zone is only a function of l_{min} , and independent of the HAZ width, since the results obtained with these two types of samples are very similar.

3.2. Stress distributions in specimens with different mis-match conditions

Finally, the results corresponding to the various HAZ undermatch levels (see Fig. 1) are presented in Fig. 6. All the results were obtained considering the weld sample HAZ2WM6 ($l_{haz} = 2$ mm and $l_{min} = 3$ mm). In this figure, it is possible to observe that the lower stress levels ahead of the crack occur for sample 8400 ($Y_0^{haz} = 400$ MPa and $n^{haz} = 0.08$), that presents the most severe undermatch conditions.

Upon analysing the results of the sample with the same yield stress undermatch conditions ($Y_0^{haz} = 400$ MPa), but with a higher hardening value ($n^{haz} = 0.16$, Sample 16400), it is possible to observe that the stress distribution rises to values close to the stress levels in sample 8500 ($Y_0^{haz} = 500$ MPa and $n^{haz} = 0.08$). These results clearly show that the fracture behaviour of the weld does not depend exclusively on the yield stress attained in the HAZ, but that it is also conditioned by the plastic behaviour of the soft material. In fact, the stress levels for sample 16 500 ($Y_0^{haz} = 500$ MPa and $n^{haz} = 0.16$) were very close to that obtained for the homogeneous sample. This shows that there is no influence of the heat-affected zone softening on the fracture behaviour of the weld if the strain hardening exponent is high, even for situations with severe yield undermatch conditions ($Y_0^{haz} / Y_0^{adj} \cong 0.7$).

The influence of the soft zone on the crack-tip stress levels completely vanishes for low HAZ yield stress undermatch conditions, $Y_0^{haz} / Y_0^{adj} \geq 0.85$ (15% undermatch).

4. Conclusions

In order to investigate the influence of the HAZ softening on the fracture resistance of welds with cracks in the WM centre line, a large variety of weld geometries and undermatch conditions of the heat-affected zone mechanical properties relative to the welding metal and base material, were addressed in this study. It was possible to conclude that an important decrease in the stress levels ahead of the crack tip can occur for severe HAZ undermatch conditions. For a certain HAZ undermatch level, the magnitude of the stresses ahead of the crack tip depends exclusively on the position of the crack tip in relation to the soft zone, nonetheless, it is independent of the soft zone extension (heat-affected zone width). The stress distribution is also influenced by the strain-hardening capacity of the soft material.

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