

Fracture mechanics based modelling of failure in advanced high strength steels

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Abstract

In the last decade, the favorable properties of the press hardening process for advanced high strength steel (AHSS) have increased the demands concerning passenger safety and lightweight design. AHSS show excellent mechanical properties from e.g. tensile test measurements, but it has previously been shown that results from tensile elongation or energy calculation of un-notched and smooth specimen are not appropriate to classify the crash behavior of steel grades. This is because they completely underestimate the post-uniform region from start of necking to failure. Another issue, the mechanical behavior of a notched or cracked component is different than a smooth and un-notched component. If the mechanical behavior in some loading is dominated by crack propagation, it should be rationalized in terms of the materials crack propagation resistance. Therefore, the evolution of the material property that controls crack propagation, i.e. the fracture toughness, is an interesting approach to evaluate loading and deformation of AHSS. Process modelling including fracture toughness depending properties gives valuable information and additional understanding of fracture behavior and crack propagation mechanisms in AHSS components. Fracture toughness in thin sheets can be readily measured through the application of the Essential Work of Fracture (EWF) methodology. The damage evolution law can be specified in terms of fracture energy (per unit area) or in terms of equivalent plastic failure strain as a function of triaxiality and lode angle. In this work, DENT test samples have been experimentally evaluated and finite element simulations of the DENT tests have been performed. By this approach the numerical study includes mechanical response of AHSS specimen including sharp cracks. In the numerical model, the J -integral was evaluated using the virtual crack-tip extension (VCE) method. From the comparison of the numerical and experimental results of load-displacement for different ligament length cases it is obvious that there are in agreement. Also, the numerically obtained value of fracture toughness J_c , is in agreement with the experimentally measured value of essential work of fracture w_e .

When finite element based fracture mechanics is applied to practical design, the fracture toughness can be used as design criteria. One appealing property of the evaluation of the J -integral is that it can be evaluated from the far field solution, which facilitates computation as many numerical errors arise close to the crack tip. Evolution of stress- and strain field, plastic zone, J -integral value and other mechanical properties is interesting to study with the combination of experimental and numerical investigations.

Keyword: Finite element analysis, Fracture toughness, Failure, Essential work of fracture

Introduction

Customer desires and demands from legislative authorities are the main driving forces behind development in the automotive industry. Today, the automotive industry focuses on reduced fuel consumption and increased crash safety. Furthermore, legislation has restricted the emissions standards for vehicles, and has assigned the need for higher safety standards. Reduction in fuel consumption and emission of carbon dioxide can be achieved by reducing the vehicle mass. The use of high strength steel also known as Advanced High Strength Steels, (AHSS) allows a decrease in component weight as strength offer a reduction of blank thickness. To meet future demands, better use of material is important e.g. reduce weight and improve crashworthiness in future vehicles. Within automotive design, accuracy will be important and development of numerical methods, models and optimization of components and safety systems are desired. A better knowledge on the limits of strength, ductility and failure of materials are of major importance and have to be more precisely determined. Also, characterization methods with high precision are needed to both calibrate and validate the numerical models. For components made of AHSS with high strength (>800 MPa) at times unexpected cracks appear during e.g. forming or crash testing. Furthermore, known from cold forming, cracks may nucleate and propagate from edge irregularities, typically in notched areas, around punched and trimmed regions. Experimental discoveries show that a combination of high strength and modest ductility of AHSS promotes the nucleation of cracks that can grow and became large cracks. This point toward a change in the design approach of structural components made of very high strength steels: a defect tolerant design should be used instead of the ductile design, usually followed in conventional steel sheet grades.

Fracture toughness can readily be measured in thin materials through the application of the J -integral or Essential Work of Fracture (EWF) methodology. The J -integral is a path-independent contour integral equal to the energy release rate in a cracked, non-linear elastic body. The method is one of the most used and fully defined in the ASTM E 1820 standard. It characterizes completely the crack tip stress-strain field when sufficiently small scale conditions prevail, i.e. the Fracture Process Zone (FPZ) is small [1, 2]. EWF on the other hand is based on the idea of Broberg [3-5] that for ductile fracture, the energy can be separated in two terms: one related to the plastic work of the region, W_p , and other related with creation of new surfaces the actual fracture W_e . A variety of different failure models is available but in many applications a component is assumed to have failed if a fracture criterion is fulfilled and the element is deleted. To fully predict component process performance it is of interested to calculate the energy absorption during crack propagation. A first study at low test speed was conducted by Casellas et al. [6]. For study stretch-flangeability and edge crack resistance in AHSS, EWF is used in [7]. Many authors addressed the equivalence between J -integral and the EWF methodology and found good agreement between the values of J_C and w_e , see [8,9].

In the present paper, numerical modelling and simulation is used to determine the fracture toughness J_C in AHSS steel specimen. Numerical results are validated against experimental measured toughness via EWF measurement determined from load and elongation response of double-edge-notched-tensile (DENT) specimens. The aim of this paper is to investigate the possibility to use numerical methods to determine fracture toughness in AHSS material. To compare how J_C and w_e agree between numerical calculation and experimental investigations is another aim.

Essential work of fracture and J-integral

The essential work of fracture was invented in the 80s to characterize fracture toughness in ductile materials and especially for thin sheets. In the experimental procedure by Cotterell and Reddel [8] and Marchal and Delannay [9], it is proposed that the total work of fracture (W_f) during the ductile fracture can be separated into two components: (i) the essential work of fracture (w_e) spent in the fracture process zone, and (ii) non-essential plastic work (w_p) dissipated in an outer region as a result of plastic deformation. The material in front of the crack tip, i.e. in the ligament, have to be completely yielded and the plastic zone is confined to the notched ligament, then the plastic work performed for total fracture is proportional to the plastic volume at initiation and the work performed at the fracture process zone is proportional to the fractured area.

$$W_f = w_e L t + w_p \beta L^2 t \quad (1)$$

Here, β is a shape factor that depends on the shape of the plastic zone, t is the sheet thickness and L is the ligament length between the two notches. That is, w_p and w_e scale differently with the sample size. Thus if a series of geometrically similar specimen of different size are tested then the two works of fracture can be separated. In principle any specimen geometry can be used, but for thin sheets the Double Edge Notched Tensile (DENT) specimen Fig. 1a is particularly suitable because the transverse stress between the notches is tensile so that no buckling occurs. Normalizing the previous equation by cross-section area, allow the experimental determination of the EWF.

$$\frac{W_f}{L t} = w_f = w_e + w_p \beta L \quad (2)$$

If w_f is plotted against the ligament length, a straight line with positive intercept, which is the specific essential work of fracture, is obtained. A schematic representation of the evaluation of the EWF is shown in Fig. 1b. However, there are some restrictions that must be met in order to use equation (2): the ligament area must be completely yielded before crack initiation and the ligament must be in a plane stress state. To accomplish those restrictions, the lower ligament length should be 3 to 5 times the thickness of the sheet thickness. The upper limit should not be larger than one third times the width of the specimen ($W/3$) or two times the radius of the plastic zone, r_p , in plane stress.

$$3, \dots, 5t \leq L \leq \min(W/3, 2r_p) \quad (3)$$

The sheet thickness in the present study is 1.5mm. Therefore, the shortest ligament chosen is 6mm. In order to determine the essential work of fracture with good accuracy four different ligament lengths are used. To accommodate sufficient spacing between those ligaments the specimen is designed with a width of 45mm, see Fig. 1a. This width allows the use of a ligament length of 15mm which is in accordance with the upper limit of the design guideline. J -integral and CTOD methods are usually applied in EPFM to determine fracture toughness when plasticity effects before crack propagation are not negligible. The J -integral is a mathematical expression, a line or surface integral that encloses the crack front from one crack surface to the other, used to characterize the local stress-strain field around the crack front. The property J_C characterizes the energy release at fracture instability prior to the onset of significant stable tearing crack extension. The so called J -integral can thus be evaluated on an arbitrary contour around a crack tip. Rice (1968) [2] derived J independently for a cracked body and introduced its application to general crack problems.

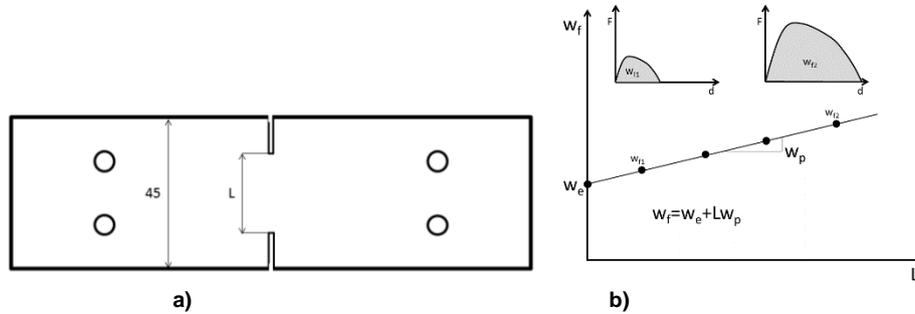


Figure 1: a) Specimen geometry and b) schematic representation of the EWF method.

In materials exhibiting a steep R curve behavior, like in very tough materials, J_C is recognized to be a conservative measurement of toughness and the J - R curve must be determined. The J -integral can be written like

$$J = \int_{\Gamma} \left(W dy - T_i \frac{\partial u_i}{\partial x} ds \right) \quad (4)$$

where $W = \int \sigma_{ij} d\varepsilon_{ij}$ is the strain energy density, where σ_{ij} is the stress tensor and ε_{ij} the strain tensor, $T_i = \sigma_{ij} n_j$ is the stress vector, where and u_i the displacement vector and ds an increment of length along the path. Because of the property of path independence of the integral it always yields the same value for any path enclosing the crack tip.

Experimental setup and numerical model

Experiment:

The study on the essential work of fracture is conducted on low alloyed boron steel in full hardened condition, resulting in a martensitic microstructure. Standard tensile tests are conducted to obtain the flow curve necessary to model plastic deformation, see Fig. 2a. An averaged test result is shown, which is also used for the finite element model. Specimens are cut in transvers to the rolling direction of the blank. In total five notch lengths ranging from 6mm to 16mm are produced using electrical discharge machining (EDM). Advantages of this method are straight cutting edges without influencing the heat treatment. The specimens undergo prior to tensile testing a procedure to create a fatigue crack starting from the notch. Polishing the surface of the specimen allows to track the crack growth, a fatigue crack length of approximately one millimeter is desired. The test for the determination of the EWF is conducted in a standard tensile test machine under quasi-static loading conditions, force and elongation are recorded continuously during the test.

Numerical model:

The nonlinear computational code LS-Dyna v971 R9.1.0 is utilized for FE-modelling and simulation of the DENT specimen test. Finite element models for all five ligament lengths are used to determine the value of the J -integral. A tool implemented in the freely available post-processing

tool LS-PrePost is used for this purpose. In the framework of this paper only a brief outline of the method is given, for the details on the implementation and the usage of the tool the reader is referred to [10]. To evaluate the J-integral, Eq. (4), in a finite element framework the contour integral is transformed to a surface integral. According to [10] this can be done by the use of the virtual crack extension (VCE) method. This is a “virtual shift”, without altering the stress state, of the crack front in the crack direction. Mathematically this method can be expressed as

$$J = -\frac{1}{\Delta A_c} \int_A (W \delta_{,i} - \sigma_{ij} u_{j,1}) q_i dA \quad (5)$$

where ΔA_c is the virtual increase in crack area. Implicit integration is applied in the numerical calculation of the DENT-test. To facilitate calculations, symmetry condition on the edge normal to the x-direction is applied. Further boundary conditions are a constraint in y-direction at the lower edge and prescribed displacement at the upper edge. Nodal displacement representing a gauge length of 50mm and extraction of sectional forces are used to compare the load-displacement response of the FE model to experimental results. The DENT specimen is modelled using Belytschko-Tsay elements (type 2 in LS-Dyna), the fatigue crack is modelled by duplicated nodes. The mesh is structured around the crack tip although deviations from a circular path is permitted. In Fig. 2b the mesh for one ligament length is shown, the meshes for the other ligament length are identical near the crack tip. For demonstrative purpose the process time step in Fig. 2b is chosen in a way that the opening of the fatigue crack is visible, the machined notch is visible in the right third of the image. For the J-integral computation in light blue one contour is indicated, see Fig. 2b. The material model chosen uses von Mises plasticity, i.e. MAT_24 in LS-Dyna.

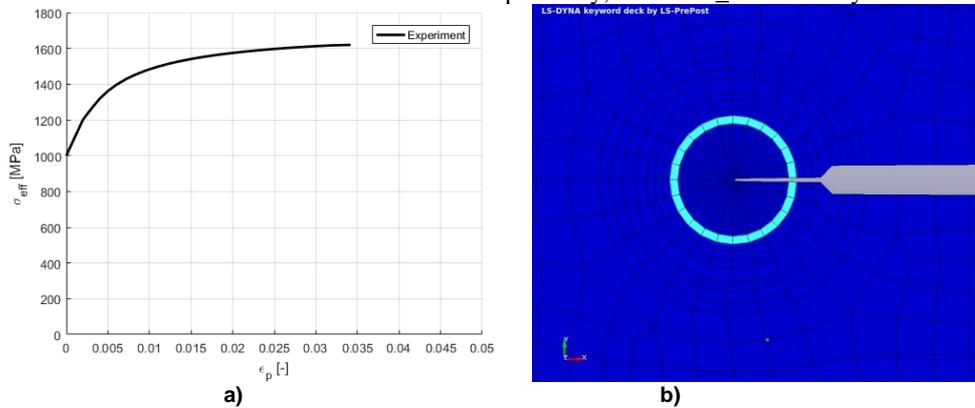


Figure 2: a) Experimentally measure hardening curve used in the numerical model. b) The mesh around the crack tip with one of the contours for J-integral computation is shown.

Results and discussion

In the numerical simulation the specimens are loaded to the onset of crack propagation. The numerical model does not include the crack propagation part. Comparisons of the numerical and experimental results for the different ligament lengths have been done, and the load displacement

for the different cases is shown in Fig. 3. An obvious difference is shown at the end of the loading response, when the crack is onset for the experimental test. Anyway, plasticity makes the response nonlinear for the numerical model but as the crack propagation is not included the stiffness is not decreased as much as for the experimental measurement. The overall behavior of the numerical model show fair agreement with experimental measurements for all cases.

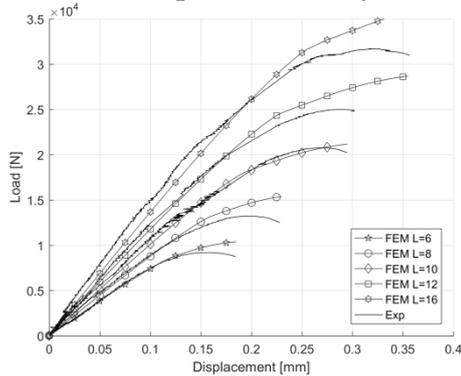


Figure 3: Comparison between experimentally measured and numerical result of the load-displacement for different ligament length.

An advantage of using simulations to mimic the DENT-test, is that the stress field in the specimen can be studied and especially interesting is to study the evolution of the stress field in front of the crack tip. One condition for the reliability of the EWF-method is that the ligament is fully plastic before the onset of cracking. Initially, the stress is zero everywhere in the numerical model. As soon as the loading start a stress field builds up. By checking the stress distribution at different loading states the evolution and the plastic zone can be studied.

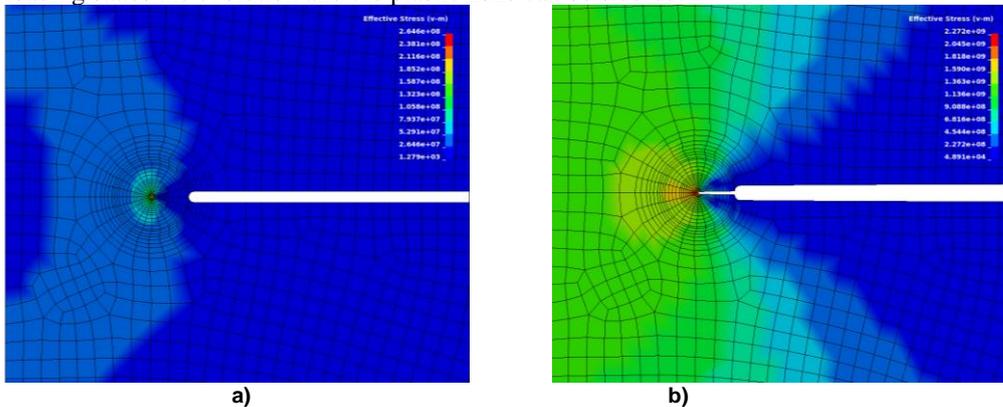


Figure 4: The von Mises stress around the crack tip is shown for the two loading states a) in the beginning of the loading all stresses are elastic and below the yield limit and b) close to the end of the loading where a fully yielded ligament in region in front of the crack tip is shown.

In the beginning of the loading all stresses are elastic, and close to the end of the loading a fully yielded ligament is shown, see the von Mises stress illustrated in Figs. 4a and 4b above. From the

experimental analysis using the EWF-methodology the value of w_e is obtained by linearization of the experimental values, see Fig. 5. The relation $w_e = J_c$ have previous been shown by many authors, see e.g. [8,9]. In the numerical simulations, the evolution of the J -integral value is calculated during loading for DENT specimens of different ligament length. The J -value at the onset of crack propagation is defined as the J_c value for the specific ligament length. As the definition of J_c say, that there is a risk for crack growth if the energy release rate value J_c is exceeded. To define a value where the crack propagation is onset experimental data on the force displacement presented in Fig. 3 is used. In this work, we have defined $J = J_c$ at the point when the maximum value of experimental load-displacement occur. For a ductile material it is difficult to know exactly when the crack is onset as this is more or less a plastic process with a stable crack growth. This definition might not be exactly accurate and the true value of the crack onset can be just before or after the maximum force value.

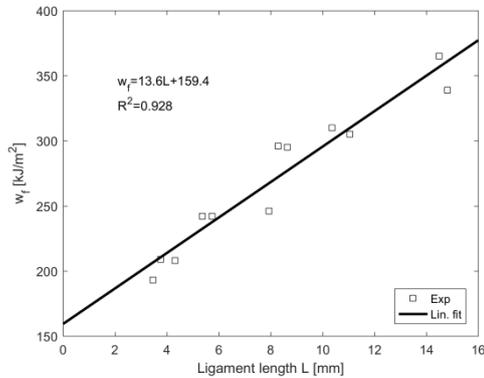


Figure 5: Experimental data linearly fitted by the EWF-method to equation (2) resulting in a value of $w_e=159.4$ kJ/m².

In Table 1 below the calculated J_c values for different ligament length is presented. Comparing the numerically calculated J_c -value with $w_e=159.4$ kJ/m², obtained from experimental measurements shown in Fig. 5, one can observe that for the smallest ligament $L=6$ mm the model under predict the J_c -value. For ligament length of $L=8$ the model predicts accurately, but for the other larger ligaments it is slightly over predicting the J_c -value. These deviations can of course come from differences in ligament length as a fatigue crack is propagated in the specimen before testing and is difficult to measure exactly.

Table 1: Numerical calculation of J_c for different ligament length.

| Ligament length, L [mm] | 6 | 8 | 10 | 12 | 16 |
|---|-----|-----|-----|-----|-----|
| Fracture toughness, J_c [kJ/m ²] | 136 | 160 | 181 | 182 | 181 |

Also the loading point for the onset of fracture is difficult to know. Even though there is some difference between numerical- and experimental results, it is shown that the fracture mechanical calculations are accurate and can be used to predict failure in AHSS steel.

Conclusion

One objective of this work was to show that numerical modelling can be used to mimic the mechanical behavior of DENT-test specimens of AHSS. Another objective of the present work was to investigate if w_e that is experimentally determined and J_c that is numerically calculated has a valid coupling for AHSS. One important conclusion is that the numerical models are in agreement with experimental results. Another conclusion is that the EWF-method can be used to estimate fracture toughness w_e experimentally and an agreement with numerical J_c is found. Numerical modelling of the fracture in AHSS is an important work and will give better insight in the evolution of the stress field, plastic zone and J can be performed. One attractive property of the evaluation of the J -integral is the evaluation from a far field solution, which facilitates computation as many numerical errors arise close to the crack tip.

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