

Determination of the essential work of fracture at high strain rates

Stefan Golling¹, David Frómeta², Daniel Casellas^{1,2}, Jan Granström¹, Pär Jonsén¹ and Mats Oldenburg¹

Abstract

During the last decades, the use of ultra-high strength steel (UHSS) has increased as its favorable ratio between strength and mass allows the design of lighter body-in-white while maintaining passenger safety. Modeling impact loads of components made of UHS steel requires reliable descriptions of the material deformation and fracture behavior.

Traditional stress or strain based fracture criteria are used in finite element modeling. A different approach in modeling fracture in components uses the fracture energy as a model parameter.

Fracture toughness is difficult to measure in thin sheets; a method termed Essential Work of Fracture (EWF) provides the possibility to determine the fracture toughness in sheet metal. With knowledge of the fracture toughness the understanding of fracture behavior and crack propagation in ultra-high strength steel can be increased. The obtained EWF is related to the fracture energy and can be used in numerical models as a material parameter.

In the present work results from preliminary testing are shown and a discussion on cross-head speed and strain rate in the critical specimen cross section is given. The use of digital image correlation provides information about the displacement field in the vicinity of the notch and hence about the strain- and strain rate distribution. Furthermore, the difficulties in reliable measurement of force and elongation in high speed tensile testing machines are elucidated. Issues encountered during the development of the high-speed DENT specimen are not limited to the specific geometry presented in this paper.

The present work aims at the development of a test specimen to obtain the Essential Work of Fracture (EWF) at high test speed. This work contributes to the overall goal to model fracture behavior and crack propagation, dependent on the strain rate. For the investigation, a high-speed tensile testing machine equipped with an in-house developed load cell and an optical elongation measurement system was used with a high-speed camera to obtain data for digital image correlation.

Keyword: Double-edge-notched-tension (DENT), essential work of fracture (EWF), high-speed

1 Introduction

Developments in the automotive industry are driven by customer desires and legislative authorities. Legislation has restricted the emissions standards for vehicles, and has mandated the need for higher safety standards. The emission of carbon dioxide is directly related to fuel consumption, and the reduction in fuel consumption can be achieved by reducing the vehicle mass. The use of high strength steel allows the reduction of blank thickness and hence a decrease in component weight.

Broberg [1-3] suggested that the non-elastic region at the crack tip can be divided into two regions, an end region where the fracture process takes place and an outer region where plastic deformation accommodates the large strains of the end region. In ductile material, the outer region where plastic deformation takes place is large compared to the end region. In the case of thin sheets made of ductile material, the end region can be identified with necking. The work performed in the end region can be considered autonomous and therefore be seen as a material constant. This material constant is in literature termed essential work. In thin sheets plane stress is a valid assumption but in this case the necking region is dependent on the sheet thickness. Hence, the essential work is not a true material constant as it has a dependency on the sheet thickness. The plastic deformation in the outer region is dependent on the geometry of the test situation. Therefore, the associated plastic work is not a material constant.

In the simulation of crash relevant components, it is essential to determine when failure of the material initiates. A variety of different failure models are 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 facilitate a component, it is of interested to predict the energy absorption during crack propagation. A first study at low test speed was conducted by Casellas et al. [4].

In the present paper, an experimental setup consisting of a high-speed test frame and a high-speed camera is used to determine the load and elongation response of double-edge-notched-tensile (DENT) specimens. The obtained data is used to calculate the essential work of fracture. The aim of this paper is to investigate experimental settings and specimen design to reliably measure load and displacement of DENT specimens at high test speeds. The EWF evaluation demands that the ligament has fully yielded prior to fracture. This requirement is monitored using digital image correlation (DIC) strain measurement. General issues of tensile testing at high cross head displacement rates and high strain rates are addressed as well.

2 Fracture theory of deep edge notched sheet specimens

The essential work of fracture is experimentally evaluated by following the methodology proposed by Cotterell and Reddel [5] and Marchal and Delannay [6]. 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 consequence of plastic deformation. If the material in front of the crack tip, i.e. in the ligament, is 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.

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

Where 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 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, allows the experimental determination of the EWF.

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

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. 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 [5].

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

The sheet thickness in the present study is 1.5mm. Therefore, the shortest ligament chosen is 8 mm. 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 45 mm, 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.

The high-speed test machine set the remaining geometrical dimensions for the specimens which are outlined for clarity. The lower part of the specimen has the same width as the lower clamping, the hole is for the bolt which aligns the specimen and applies pressure on the specimen, and the pressure causes a frictional force. If the frictional force is too low during testing the specimen has a tendency to fail at the hole. The width of the upper part of the specimen is chosen in accordance with the width of the upper grip. The length of the specimen is necessary to accelerate the cross-head before the specimen is clamped in the grip.

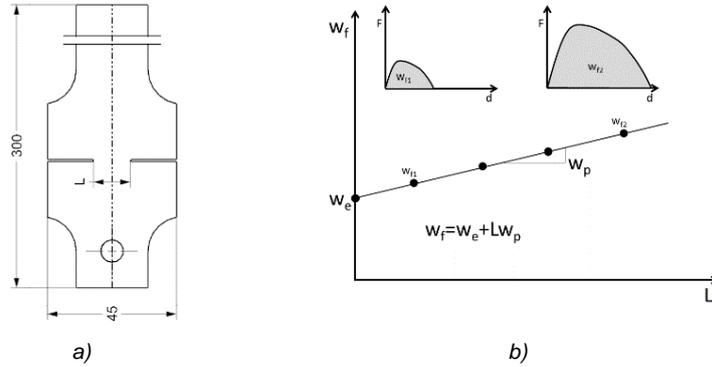


Figure 1: a) Specimen geometry, notch width 0.3 mm and notch tip radius 0.15 mm, b) schematic representation of the EWF method.

3 Determination of strain rate

The influence of the strain rate on the plastic flow of steel has been a subject of research under long time; see for example Zener and Hollomon [7]. The strain rate is the change in strain of a material with respect to time. If a straight tensile test specimen is loaded the strain rate can be expressed with a single number.

$$\dot{\epsilon}(t) = \frac{d\epsilon}{dt} = \frac{d}{dt} \left(\frac{L(t) - L_0}{L_0} \right) = \frac{v(t)}{L_0}$$

Here $v(t)$ is the cross-head speed, L_0 the initial gauge length and $L(t)$ the length of the specimen at time t .

In more general loading cases, when the material is deformed in various directions at different rates, the strain and therefore the strain rate at a point within the material cannot be expressed by a single number. For such cases, the rate of deformation is expressed by a tensor that expresses how the relative velocity of the material changes when a point moves by small distance in a given direction. This strain rate tensor can be defined as the time derivative of the strain tensor.

For notched specimens, the strain rate varies depending on the position in the specimen. For classification of test speeds, it is convenient to describe the displacement rate of the cross-head of the test machine. Applying the cross-head speed to a measurement length allows calculating a strain rate but this value might be misleading. The material experiences in the local region of the notch and at the tip of a crack different, much higher, strain rates than would be measured using a standard extensometer length of $L_0 = 50$ mm. The strain rate concentration for DENT specimens at the root of the notch is discussed by Noda, et al. [8].

Using digital image correlation, it is possible to compute the local strain rate at a measurement point. The size of the region where this value applies depends on the chosen facet and step size. In the present study, the available image resolution for the chosen camera speed is 640x290 px, a

facet size of 12 px and a step of 2 px are chosen. The strain is calculated within a 3x3 matrix representing three adjacent facets. Images taken with the high-speed camera have a time stamp and hence the time increment between two images is known. Using the calculated strain values and the time increment it is possible to determine the strain rate on the specimen surface.

4 Experimental setup

Instron High Strain Rate VHS system, utilizes advanced servo-hydraulic and control technologies designed for a wide range of high strain rate and high-speed test requirements. The test frame capacity is dimensioned for loads up to 100 kN and velocities up to 25 m/s. An operating pressure of 280 bar results in high acceleration velocity and load performance. The lower clamping is an in-house development and consists of a combined grip and load cell to optimize the linearity of the load signal at high frequency which occurs at these high speeds. The load cell also has a built in system for compensating for the additional masses that are connected to it, in this case the specimen. The load cell clamping consists of two parallel surfaces and a bolt which applies load on the specimen head and positions the specimen in a straight aligned position relative the upper grip. The upper grip is comparable to a standard double wedge clamping system but modified to allow for acceleration prior to clamping. The upper clamping grip is set under pretension with loaded bolts and ejector rods are used to push out the holding mechanism to grip the specimen when the desired speed of the upper clamping grip is reached. The specimen upper part then accelerates from zero to the chosen speed of the upper clamping grip in less than 0.5mm.

Images for DIC are taken by a high-speed camera. The Phantom v1610 provides a widescreen CMOS sensor and delivers 16000 frames-per-second at full resolution of 1280x800. At reduced resolutions, the camera offers frame rates of up to 647000 fps. The sensor ensures high light-sensitivity which is essential in ultra-high-speed imaging. The camera is equipped with a large internal high-speed memory and pictures of tests are transferred to a computer by an Ethernet connection. The camera runs in a continuous recording mode and a trigger signal is used to identify pictures taken during the test.

ARAMIS is commercially available digital image correlation (DIC) software developed by GOM. It is a non-contact and material-independent measuring system based on DIC. It offers a stable solution for full-field and point-based analyses of test objects. The system performs measurements regardless of the specimen's geometry and temperature. The ARAMIS measured data is used to determine material properties. These material properties are typically used as parameters for numerical simulations and contribute to the calibration and validation of finite element simulations.

In the present study images from the high-speed camera are imported into ARAMIS and evaluated in the region of the ligament.

The results from this evaluation allows the determination of three factors, (i) for the determination of the essential work of fracture it is necessary to guarantee that the complete ligament length is in a plastic state, (ii) the strain rate at fracture in the region of crack propagation is of interest, and (iii) a virtual extensometer can be established.

The measurement of the elongation of the test specimen during loading is in static or quasi static tests performed by mechanical or optical extensometers. Using a mechanical extensometer is not possible in high-speed applications due to inertia of the clips attached to the specimen and also because of the long movement of the actuator which would damage the extensometer. Optical measurement systems are better suited for the present test setup but have the drawback of a measurement uncertainty of up to ± 0.1 mm. The measurement uncertainty maybe neglected for most test situations, deep notched specimens show low elongation and the possible error might influence the result significant. Hence, the use of a virtual extensometer created in ARAMIS is an accurate and reliable alternative.

In the present study, the cross-head speed of the high-speed machine is set to 0.5 m/s, an initial study was conducted with test speeds ranging from 0.15 to 6 m/s. The choice of the test speed is governed by the obtained strain rate and the number of images possible to obtain during the test. Limiting factor is the sample rate of the high-speed camera. Increasing the number of frames per second leads to a decrease in resolution, the resolution cannot be decreased below 640x290 px due to the virtual extensometer length of 16 mm. The choice of the virtual extensometer length is governed by the image size at the necessary camera speed. For EWF testing the length of the extensometer has only a minor impact as the deformation of the specimen is confined to a small region. The framerate at a resolution of 640x290 px is 72k which corresponds to a shutter time of 13.9 μ s. The settings for the DIC evaluation in ARAMIS are set to facet size of 12 px and a step size of 2 px. The speckle pattern on the specimen surface is created by sandblasting, no additional spray paint was necessary.

5 Results and discussion

This section presents the findings of an initial study on the possibility of determining the essential work of fracture at high test speed.

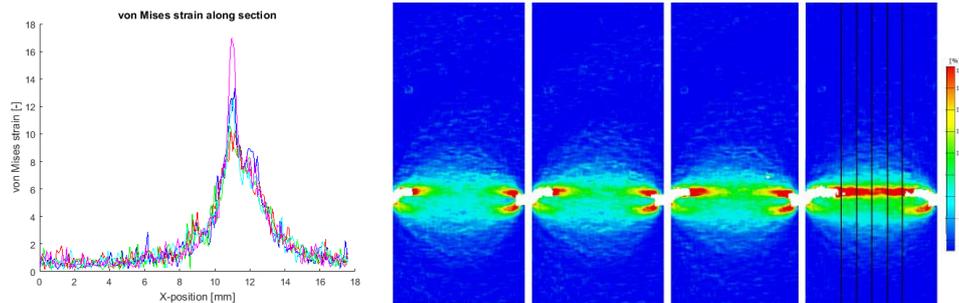


Figure 2: The von Mises strain along five sections of the DIC evaluation and the strain distribution in the vicinity of the notch. The sections are indicated by black lines in the picture to the right. The DIC images show the last four images prior to full fracture, time step between the images is 13.9 μ s.

The deformation of the specimen is localized into a narrow section in the vicinity of the notch. In Fig. 2 the von Mises strain is extracted along five equally spaced lines along the evaluated DIC

image, the data plotted is taken from the last image prior to fracture i.e. the picture furthest to the right. The last four images taken prior to full fracture are shown, deformation localizes into a narrow band where the crack is going to propagate. The shape of the plastic zone, which can be approximated with a circle with the diameter of the ligament length, is visible although the vertical parameter has smaller plastic strain values. Hence, the requirement of a fully yield ligament cross-section is fulfilled.

The goal of the test at elevated speed is to increase the strain rate in the fracture process zone. DIC is used to estimate the strain rate at a local level. Strain rate calculation is performed using the strain values and the time step between images. In notched specimens, the strain rate is varying with the position in the sample and with the test progress. In Fig. 3 the same sections as in the previous figure are used to display the strain rate in longitudinal direction, the data shown corresponds to the last image prior to full fracture which corresponds to the picture furthest to the right.

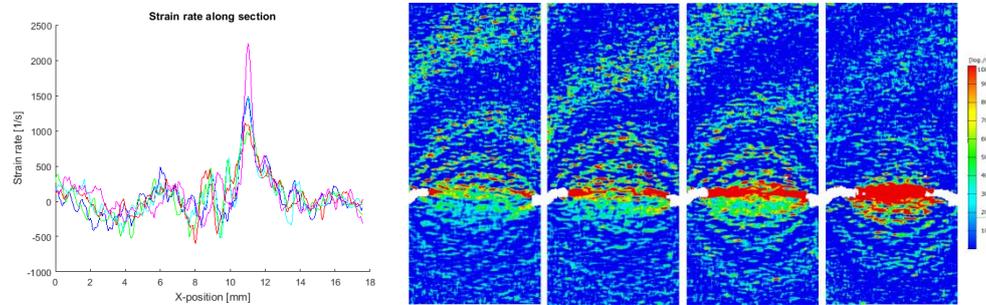


Figure 3: The strain rate along a section of the DIC evaluation and the strain rate on the evaluated surface of the specimen. The DIC images show the last four images prior to full fracture, time step between the images is $13.9 \mu\text{s}$.

The strain rate in the fracture zone is significantly higher compared to the remainder of the specimen. In Fig. 3 strain rates below zero are visible; this effect is explained by elastic waves in the specimen which cause a spurious strain rate with values below zero. In the images, the waves can be seen as semi-circle patterns originating from the ligament. A single wave cannot be followed by images of the high-speed camera as the wave propagation speed is by far higher compared to the time step between images. Using this approach, the local strain and strain rate can be determined on point or line level. Another method is to define an area and average the strain rate on it. An example for such a result is shown in Fig. 4a. The chosen area is 4mm wide and ranges over the complete ligament length; it is plotted for the complete duration of one test. During loading the strain rate increases and exceeds 1000 /s prior to fracture. This approach provides a single number valid for the selected area for every time step with the drawback that non-deforming areas contribute to the result.

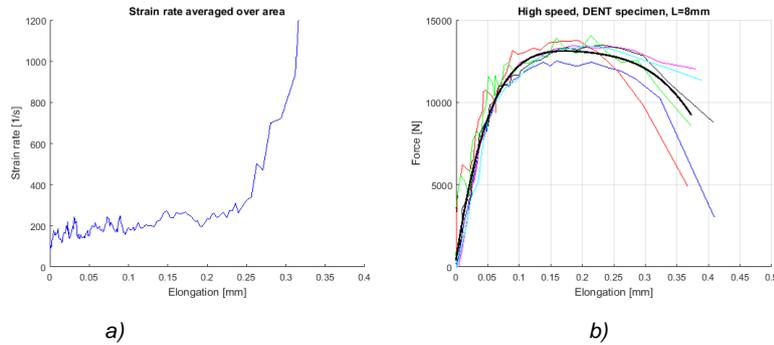


Figure 4: a) The averaged strain rate over an area across the ligament, b) Experimental result of the EWF testing and fitted average result.

The present studies aim is to determine experimental setup and specimen geometry for the determination of the essential work of fracture at high-speed. Initial tests were conducted at different cross-head speeds. It is concluded that a cross-head speed of 0.5 m/s is sufficient to obtain a local strain of 1000 /s. Higher cross-head speeds are possible but reduce the number of images available for DIC, with fewer images the number of data points for the determination of the elongation decreases, also the point of final fracture may not be captured. Limiting factors for the number of usable pictures is the necessary illumination of the specimen and the resolution of the camera at higher speeds. Increasing the number of frames per second reduces the size of the image. If the image is too small the virtual extensometer cannot be placed across the plastic zone.

The use of a virtual extensometer in Aramis is justified by the small elongation to fracture. A conventional optical measurement system captures the elongation but a higher deviation has been found during this study, compared to the approach used.

For the chosen cross-head speed the longest ligament length was tested and evaluated according to the presented method. The result is not presented here due to the number of tested specimens which do not allow evaluating the EWF with proper statistical measures. From this qualitative test, it is concluded that the method works as well for this ligament length but that the lower clamping is a critical point. The clamping force necessary is higher compared with the other samples; a special sample preparation and a modified clamping bolt solve the issue with this ligament length.

For ligament length of 8 mm the number of samples is sufficient to evaluate the EWF, test results and a fitted function is displayed in Fig. 4b. In the figure, the measured data of six samples are displayed in color, the bold line is a polynomial function fitted using the least squares method. Integration of each measured curve results in a total work of fracture of $w_f = 355 \pm 18 \text{ kJ/m}^2$, integrating the polynomial function gives a value of $w_f = 347 \pm 4 \text{ kJ/m}^2$. For the determination of the values of w_e and w_p at least two more ligament lengths are necessary.

The present work describes an experimental setup for the measurement of the EWF at high strain rates. This initial study is intended to develop the specimen geometry and the setup of the equipment. To increase reliability of elongation measurement a virtual extensometer using DIC is ap-

plied. The double notched specimens showed elongation of about 0.3-0.4 mm which is small compared to the measurement accuracy of standard optical system. A further advantage of DIC is that it allows the determination of the strain and strain rate on a local level. Adjusting the lower clamping allows the testing of samples with a range of ligaments from six to fifteen millimeters, this range is sufficient for a reliable determination of the essential work of fracture.

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Affiliation

- [1] Division of Solid Mechanics, Luleå University of Technology, 971 87 Luleå, stefan.golling@ltu.se
- [2] Fundació CTM Centre Tecnològic, Plaça de la Ciència 2, 08243 Manresa, Spain