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Analyzing the properties promoting shear bands and damage initiation in 3-point bending of ultra-high strength steel

Robert Dowding[a,*], Christophe Pinna[a], Hassan Ghadbeigi[a], Didier Farrugia[b]

[a]*The University of Sheffield, Mechanical Engineering Department, Sheffield, S1 3JD, United Kingdom*
[b]*Tata Steel Europe, Rolling Finishing & Measurement Department, United Kingdom*

* Corresponding author. *E-mail address:* rdowding1@sheffield.ac.uk

Abstract

Ultra-high strength steels (UHSS) have been developed to reduce the weight and increase strength capability of high value products such as crane structures. The bendability of UHSS steels has limited its application in production as their yield strength has increased, the bendability has been found to reduce with the reduction of tensile ductility. In this paper, the material properties affecting bendability in UHSS have been investigated and factors have been identified by analysing specimens pre and post bend testing [1-3] using a combined approach of in- and ex-situ small mechanical testing, Digital Image Correlation (DIC), modelling and characterisation. The propagation of shear bands in bending has been identified as the mechanism promoting damage in the tensile face to occur in the bending of steels. Identifying these factors combined to promote failure is of great importance while also developing a practical approach to identifying procedures to improve bendability.

A small-scale bend test with new tooling and specimen geometry has been conducted inside the chamber of a Camscan SEM to observe the propagation of shear bands and damage initiation at the scale of the microstructure. Micrographs produced during the test were processed using DIC to study shear band formation in relation to strain distributions.

Using these techniques shear bands and damage are observed at the tensile surface of the bend test. The strain localises in shear bands in a bifurcating pattern from the tensile surface in bending. Damage initiates at the surface where these shear bands intersect promoting a high strain at the surface. This damage promotes the shear bands to move through the sub-surface promoting further deformation then promoting more damage when the plasticity is exhausted. In this test a large 5µm inclusion is observed to interact with shear bands and seen to affect the damage propagation of the specimen and localise high strains at a region local to it. This region is where the failure originates from. Further analysis of the interaction between subsurface properties and the localisation of strain and shear bands will be studied.

Keywords: "Shear bands, 3 point bending, digital image correlation, bendability, ultra-high-strength steel, microstructure ;"

1. Introduction

The development of UHSS steel has enabled the reduction in weight of structures in crane booms. This has been achieved by increasing in the yield strength of the steel. While this has lowered the weight and associated carbon emissions for the product life, the bendability of the steel requires improvement to reduce failure during three-point bending. To understand this better, a study into the initiation of shear bands and their development into damage has being performed.

Shear bands originate from a plastic instability that localizes large shear strains in a thin band when material is deformed. This then leads to failure. In bending, shear bands have been found to be prevalent in the tensile region [4].

During bending of standard bend test specimens, damage occurs at the outmost layer at the positive stress region where the triaxiality is highest and the largest plastic deformation is

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observed. A new geometry and test methodology have been developed to facilitate the bending induced damage at lower required load and displacements that makes the in-situ investigation of UHSS steels more feasible.

2. Methodology

To observe damage in in-situ bend testing a new bend test specimen geometry was required to promote shear bands and damage on the observed face during bend testing. An in-situ bending rig with a load capacity of 5kN and total displacement range of 10 mm was used in this study. Therefore, a parametric study was conducted by changing the critical features of the standard bend sample in such a way to achieve local plastic deformation, damage initiation and evolution in the region of interest in the sample. Fig. 1 shows the geometry developed to promote these properties.

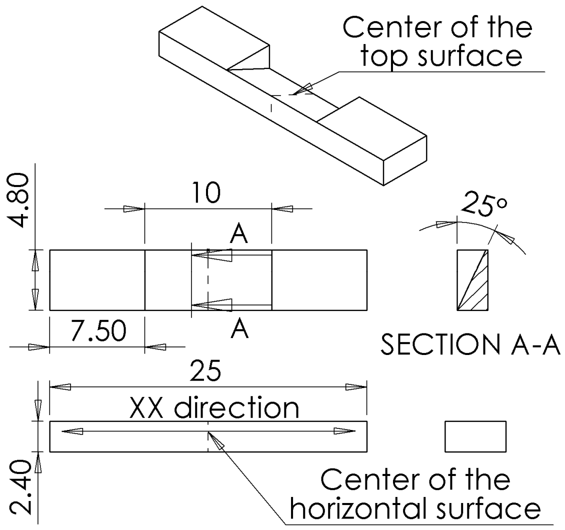

Fig. 1. Angled bend test specimen geometry.

As a three-point bend test is performed the strain is concentrated at the center of the acute edge. This is due to an anticlastic profile across the width. This combined with the angled shape further intensify the strain at the acute edge Finite Element Modelling (FEM) using an elasto-plastic continuum model using data from tensile tests with the UHSS with a chemical composition of 0.1% C with Cr/Mo/B of which the bending sample is of identical material. In the FEM the boundary conditions are set that the specimen is held between tooling with a Coulomb friction coefficient of 0.3 in a static model. A displacement on the former through the specimen is applied for the full displacement of the Deben module of 10mm. By varying geometries to optimize bending geometry by varying the thickness over the width, this was then sized to function within the load constraints of the Deben bend test module. This allowed the analysis of strain development through the test and compare with other geometries by performing a study using FEM it was found that using an angle of 25 degrees produces an optimal profile for promoting damage at the observed face due to high strain localization in Fig. 3

Using the geometry and tooling as shown in Fig. 2. a bend test is performed using a Deben bend in-situ module within an SEM such that the microstructure can be observed during the bend test.

The specimen is manufactured by Electrical Discharge Machining, EDM to minimize the effects of residual stresses from machining and produce the geometry required to promote strain localization at the edge. The angled edge is produced with EDM to retain the face as close as possible to the surface of the plate. The bottom surface of the specimen is machined to reduce bend test loads on the module.

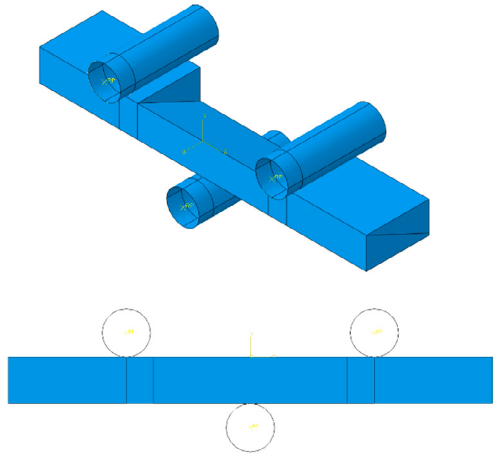

Fig. 2. FEM of tooling in contact with the specimen, orthogonal view and view of the horizontal face as seen from the SEM.

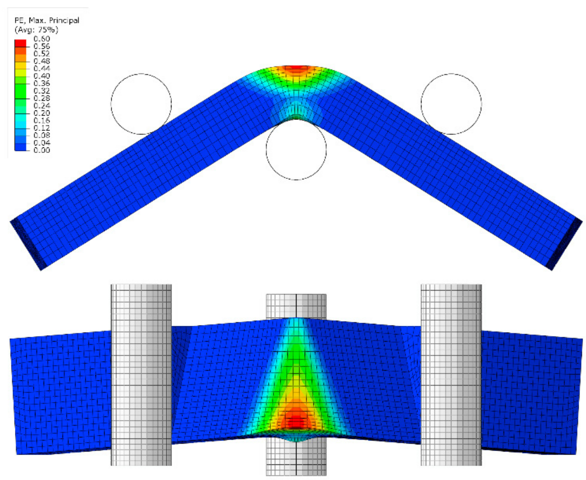

Fig. 3. FEM demonstrating strain as PEEQ deformed at 3mm of displacement.

To prepare the specimen, grinding and polishing is performed on the specimen's horizontal face, down to 1μm diamond suspension. The sample is then etched in 2% nital to reveal the microstructure. The SEM is operated with the secondary electron (SE) detector for observation of the surface microstructure and initiation of shear bands. A bend test is performed with interruptions to allow micrographs to be obtained while positioning each micrograph in the same relative position at each interruption. This procedure enables the use of DIC software to study strain distributions in the microstructure by post processing these images.

3. Results

During the bend test high strains are observed at the center of the horizontal surface due to the angled geometry of the specimen as predicted from the FEM (see Fig. 3). By performing post processing with DIC the micrographs can have strain maps overlaid on them. In Fig. 5 strain in the xx direction is analyzed from the micrograph of Fig. 4. The tensile region of the bend test is observed, and shear bands propagate in a bifurcating mode from the surface due to localized damage from EDM cutting. The strain is concentrated at the shear bands with low strain of around 5% in areas unaffected by shear bands.

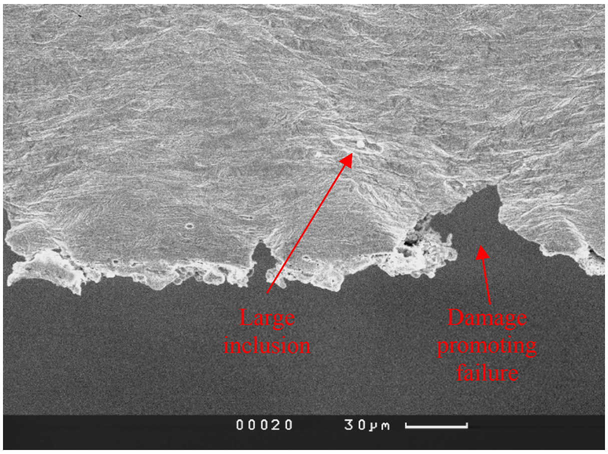

Fig. 4. Micrograph of the deformed microstructure at the center of the horizontal surface at 3mm displacement.

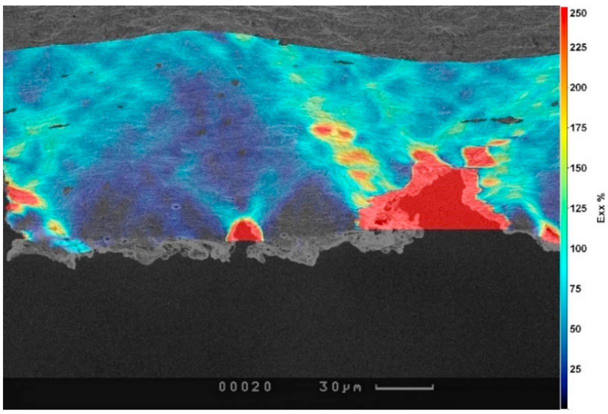

Fig. 5. Micrograph processed with DIC to produce a strain map of center of the horizontal surface at 3mm displacement.

This eventually promotes damage at the edge in Fig. 4 with only 1mm displacement damage is visible and progresses as the displacement is increased. The damage initiation was observed at the locations of shear bands with bifurcation occurring at the surface. Each shear band is perpendicular to the other at 45 degrees from the surface.

Damage initiation is located at the tensile surface with a strain in Exx of 50%. These interact with the shear bands localizing the strain near the edge intensifying the shear bands.

Once these high strains occur damage propagates by plastic tearing following the shear bands in their bifurcating mode causing the damage to change direction in Figs. 4 and 5. This is a standard characteristic in bend test damage and seen in multiple instances during the test. High strains in excess of 200% are observed at shear bands local to the large 5µm inclusion but the crack does not interact with it. This instead follows a highly localized high region of strain on the other shear band. The specimen ultimately fails due to the right most damage initiation point becoming a large crack as shown on Fig. 4.

4. Discussion

The bend test shows that the formation of damage is linked to the shear bands which intensify the strain in the specimen leading to the propagation of damage through the specimen. The localized strain at these points is relatively low at 50% Exx compared to other failures observed in the SEM [4] this is likely due to a lack of ductility from the EDM machining and the angled geometry promoting the damage to the observed face. The production of shear bands and how these interact are of greater interest.

The design study was carried out using a continuum elasto-plastic finite element model developed to optimize the bending geometry based on the distribution, at the continuum scale, of the equivalent strain which is commonly used to assess damage development. The model does not include damage or microstructural effects. Therefore, strain distributions cannot be directly compared to those measured at a very local scale using DIC with the formation of shear bands influenced by the microstructure. In 2D FEMs applying a Gurson-Tvergaard-Needleman model to promote strain localization, shear bands are found at a consistent spacing [5]. This has also been found in the experimental results where shear bands, rippling and damage are found in that order with consistent spacing between each shear band. Rippling is often reported prior to damage initiation in bending [5] so there is likely to be shear bands when this is observed. These shear bands will then localize the strain promoting the failure of the specimen.

The author believes the consistent spacing is due to the tensile face the strain localizes in regions finding a weakness over an area in strain. In FEM the effect of mesh sizing is important regarding the shear bands in some modelling hence a link to the refinement of microstructures could be linked as well as the inter-granular promotion of shear bands. This is also linked to the ratio of tool radii and specimen thickness with the former radius distributes the strain for a given thickness.

The shear bands can be seen interacting at both the surface and the subsurface. further increasing the strain the mechanism causing this will require further research.

The location of damage promoting the specimen failure is located near an inclusion. Where the shear bands initiate at a position at 45 degrees to the surface. The damage does not propagate through the inclusion even with high strain localization in the area. The interaction between the surface properties and subsurface inclusion have been observed to affect the location of damage initiation and propagation. Further tests need to be performed to statistically analyze the influence of inclusions.

5. Conclusion

Using the novel bend test geometry, a better insight into the generation of shear bands and damage can be developed. Some conclusions from the work include:

- Shear bands can be observed initating at the tensile edge of angled bend test specimen in three-point bending.
- Damage intiation and propogation is observed at the horizontal face of the tensile test surface by performing three-point bending with angled specimens.
- The interaction between the shear bands, surface rippling and damage promote the change in direction of the damage due to bifurcation of the shear bands.
- Damage initates at the surface with shear bands interacting with a large 5μm inclusion progressing to have high strains on and around the inclusion. These high strains at the surface that initiate then propogate damage appear to be influenced by subsurface inclusions.
- Further analysis of the influence of local material properties. In particular the effect of inclusions on the location of damage intation and propogation needs to be studied.

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