International Journal of Solids and Structures 46 (2009) 2750–2756

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Spatially resolved observations of strain fields at necking and fracture of anisotropic hardened steel sheet material

J. Eman [1], K.G. Sundin *, M. Oldenburg

Solid Mechanics, Luleå University of Technology LTU, SE-97187 Luleå, Sweden

ARTICLE INFO

Article history:
Received 29 October 2008
Received in revised form 28 January 2009
Available online 20 March 2009

Keywords:
Plastic deformation
Strain analysis
Necking
Localization
Mechanical testing
Fracture
Failure analysis
Speckle correlation

ABSTRACT

In this work plastic strain localization, also referred to as necking, of press-hardened ultra-high strength steel is observed using digital speckle correlation. The region of the neck is studied during tensile tests of specimens specially designed to facilitate strain localization at an inner point of the material, thus avoiding edge effects on localization and fracture. By using measurements with a length scale small enough to properly resolve the neck, its growth and shape can be studied. Furthermore, the anisotropy of the material is investigated by examining specimens cut out at different angles to the rolling direction. It is seen that the local fracture strain of specimens cut out along the rolling direction is approximately twice as high as it is for specimens cut out perpendicular to the rolling direction.

1. Introduction

Plastic forming of ductile sheet metal is a very common activity in for example today's automotive industry as well as in other mechanical applications. Also in unintentional situations such as collisions, sheet material is subjected to plastic deformations. In the beginning of the plastic process at low strain levels the state of strain is generally smooth but after this initial stage the developing strain is often localized to a narrow area. This localization is called necking and it is the prelude of fracture because a crack is ultimately formed in the neck. The most well known example of plastic localization is perhaps the forming of a neck towards the end of a standard tensile test.

The localization of strain to a limited region results in a rapidly increasing strain level within this region. This increase in strain will ultimately lead to the onset of fracture which in all practical situations is an unwanted scenario. In many technical applications it is desirable to use the materials to their limits, that is, deform them as much as possible without causing a fracture. Therefore, it is of great interest and importance to widen the knowledge and understanding of the phenomenon of necking.

Within the automotive industry crash-protecting components such as A- and B-pillars, bumper beams and side impact protections are often made from ultra-high strength steel. The purpose is to save weight at maintained or increased structural strength. In order to save even more weight, larger structures of the vehicles could be made from this type of material. However, this development requires a very detailed knowledge of the behaviour of the material, also regarding necking and fracture.

The phenomenon of necking has been studied for a long time. One goal has been to determine the entire true stress–strain relation for a material up to fracture see Zhang and Li (1994), Meuwissen et al. (1998), Zhang (1995), Ling (1996), Koc and Štok (2004), Zhang et al. (1999, 2001a,b) which is of importance for accurate simulation of large-strain applications. In sheet forming processes forming limit diagrams (FLD) are often used to predict local necking and subsequent fracture and the establishment of such diagrams includes study of the necking phenomenon under more general conditions than the conventional uniaxial tensile test. Analytical background for FLD theories can be found in e.g. Hill (1952), Swift (1952), Marciniak and Kuczynski (1967), Storen and Rice (1975), Needleman and Tveergaard (1977) and some recent experimental work is reported in Brunet et al. (1998) and Brunet and Morestin (2001).

Experimental techniques have developed rapidly during the last decade and the trend towards optical field methods is strong. An example of an older experimental work based on conventional microscopic observations of the metallographic structure during deformation is given in Carlson and Bird (1987). Examples of modern methods used in observations of plastic deformation and neck-

* Corresponding author. Tel.: +46 920 491284; fax: +46 920 491047.
E-mail address: kgsundin@ltu.se (K.G. Sundin).
[1] Swerea SICOMP AB, P.O. Box 271, SE-94126 Piteå, Sweden.

0020-7683/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsolstr.2009.03.003

ing behaviour are Brunet et al. (1998), Brunet and Morestin (2001), Suprapedi and Toyooka (1997), Gong and Toyooka (1999), Wattrisse et al. (2001a,b), Vial-Edwards et al. (2001), Quinta da Fonseca et al. (2004), Guelorget et al. (2006), Martínez et al. (2003), Labbé and Cordero (2007). It seems that digital speckle correlation (DSC) is perhaps the most commonly used full-field experimental method for studies of plasticity. This is explained by the fact that it has become available even outside optics labs and it is fairly simple to use also by investigators who are not experts in optics. It is also commercially available nowadays. This method is reviewed and evaluated in Tong (2005), Schreier and Sutton (2002), Hild and Roux (2006) and some good examples of its application in material studies can be found in Brunet and Morestin (2001), Quinta da Fonseca et al. (2004), Kajberg and Lindkvist (2004).

DSC is used in the present study with focus on investigation of the nature of necking appearing in ultra-high strength steel under tension. The region of the neck is observed in detail at a number of time instants throughout a tensile test of a specimen. This enables studies of both the growth and the shape of the neck. Strain components in the neck region are recorded during the tensile plastic process. Proper measurements of the necking phenomenon require the length scale of the measurement to be small enough so that the neck is sufficiently resolved. The dependence of different length scales in the measurements is investigated.

In order to investigate the behaviour of the material itself and not the influence from edges, a non-standard specimen shape is developed. The specimen shape is designed to produce plastic strain localization in the centre of the specimen. This causes the fracture to emanate from an interior point of the specimen, thus eliminating influence from edge effects. Also, the chosen specimen design allows the position of the fracture to be determined prior to the experiment and therefore the measurement can be focused to that region, thus enabling a higher spatial resolution.

Anisotropic behaviour regarding plasticity and fracture is common for rolled sheet material and proper understanding and modelling is essential in simulation of sheet forming processes (see Huang et al., 2000; Brunet et al., 2005; Hill, 2001). DSC is a suitable method for experimental investigation of strains in different directions and their development during loading to fracture. Strains at the centre of the neck in specimens taken at 0°, 45° and 90° to the rolling direction are studied in this work. The material in the investigation is a press-hardened ultra-high strength steel.

2. Experiments

2.1. Material and specimens

The material chosen in this investigation is an ultra-high strength steel (hardened 22MnB5) which is used in protective structures in cars. Anisotropy is introduced by the rolling process of the base material. Simultaneous forming and quenching in water-cooled tools gives the material its strength properties. Components may be loaded in such a way that fracture will not emanate from an edge and therefore it is of interest to examine fracture behaviour at an inner point. Conventional tensile specimens (SS EN 10 002-1) with a straight part are unsuitable because the edge may influence the fracture process to a high degree through irregularities, micro cracks and heat effects from the cutting process. Further, the exact position of the final fracture is unforeseeable in such specimens and since local measurement in the area of plastic localisation is the objective of this investigation, straight specimens were not used. Instead a specimen shape with a shallow notch is chosen. A varying cross section of the specimen will cause a non-homogeneous state of strain and stress but the position of the localisation and subsequent fracture is determined by the notch and thus possible to predict with high accuracy.

The suitable shape of the specimens was determined through a pilot study involving FEM-simulations and experimental verification. A plausible stress–strain relation and fracture strain criterion, determined approximately in the study, was used in the simulations and different specimen shapes were tested numerically through simulation of tensile loading to fracture. Shapes leading to localisation and fracture initiation in the inner part of the specimen are potential geometries for this research and specimens with shallow notches showed such behaviour. Lower fracture strain at the edges due to influence from cutting was not assumed in the simulation model and therefore the numerical results had to be verified by a set of preliminary experiments. The final shape of the specimens that was chosen for the rest of the investigation is presented in Fig. 1a.

For reference, conventional tensile tests using straight specimens and an extensometer are performed. There is however a slight modification to the standard straight specimen (SS EN 10 002-1). The sides are not exactly parallel but instead machined with a large radius to ensure that localisation and fracture take place within the gauge length covered by the extensometer. Geometries for both the notched and the straight specimen are presented in Fig. 1.

The conventional tensile testing of straight specimens according to Fig. 1b is performed with an extensometer length of 50 mm. Specimens taken parallel, perpendicular and in a 45° angle to the rolling direction are tested and stress–strain diagrams are presented in Fig. 2. Tests are performed on specimens with thickness *t* of both 1.2 and 2.4 mm and each test is repeated two times. All specimens are cut from sheets that are hardened in a press between flat cooled surfaces. Abrasive water cutting is used for manufacturing of all the specimens and testing is performed in the as-delivered condition without further treatment.

2.2. Experimental set-up and procedure

Local strains are measured with the method of Digital Speckle Correlation (DSC), which is a multi-point or grid method giving strain data in a large number of points over the monitored area. Speckle patterns in the form of randomly distributed black and white dots were applied to the specimens with spray painting. The experimental arrangement, sketched in Fig. 3, involves a 250 kN servo-hydraulic testing machine (Dartec M1000/RK,

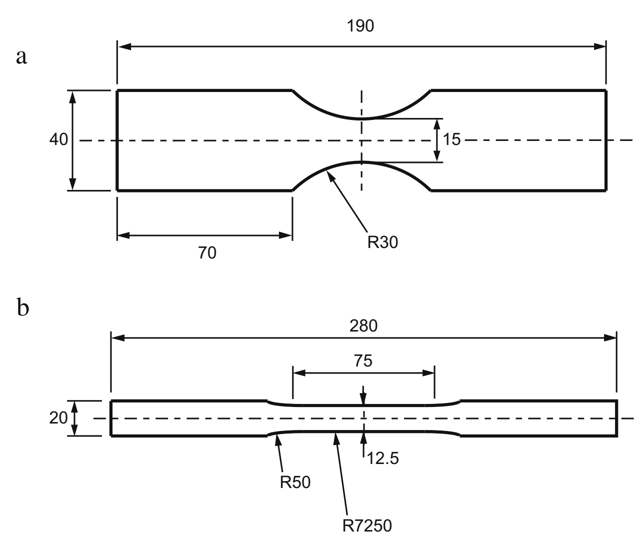

Fig. 1. Specimen shapes (a) with shallow notches and (b) conventional straight specimen.