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A study of localisation in dual-phase high-strength steels under dynamic loading using digital image correlation and FE analysis

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Abstract

Tensile tests were conducted on dual-phase high-strength steel in a Split-Hopkinson Tension Bar at a strain-rate in the range of 150–600/s and in a servo-hydraulic testing machine at a strain-rate between 10^{-3} and 10^{0}/s. A novel specimen design was utilized for the Hopkinson bar tests of this sheet material. Digital image correlation was used together with high-speed photography to study strain localisation in the tensile specimens at high rates of strain. By using digital image correlation, it is possible to obtain in-plane displacement and strain fields during non-uniform deformation of the gauge section, and accordingly the strains associated with diffuse and localised necking may be determined. The full-field measurements in high strain-rate tests reveal that strain localisation started even before the maximum load was attained in the specimen. An elasto-viscoplastic constitutive model is used to predict the observed stress–strain behaviour and strain localisation for the dual-phase steel. Numerical simulations of dynamic tensile tests were performed using the non-linear explicit FE code LS-DYNA. Simulations were done with shell (plane stress) and brick elements. Good correlation between experiments and numerical predictions was achieved, in terms of engineering stress–strain behaviour, deformed geometry and strain fields. However, mesh density plays a role in the localisation of deformation in numerical simulations, particularly for the shell element analysis.

Keywords: High-speed photography; Localisation; Dual-phase high-strength steel; Split-Hopkinson bar; Photomechanics; Elasto-viscoplasticity

1. Introduction

The high-strength and good formability characteristics of high-strength steels when compared to conventional grades make them attractive in applications involving high rates of loading combined with a demand for low weight. Typical examples include light-weight protective systems (Børvik et al., 2006), crashworthiness of

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automotive and aerospace structures (Tarigopula et al., 2006; Galvez et al., 2006), and high-speed machining. The mechanical behaviour of materials at high strain-rates is considerably different from that observed at quasi-static loading because of the strain-rate sensitivity of the material and propagation of stress waves. A standard way of characterizing a material over a wide range of strain-rate is by means of its stress–strain response. In general, the stresses and strains are estimated from the load and displacement measurements by implicitly assuming uniform fields. The data obtained through the stress–strain curve thereby has certain limitations in terms of its validity beyond the point of uniform deformation, where the strains start to localise. Under these conditions, conventional strain measurements will not represent the true behaviour of the material and can only give an indication about an average strain. Furthermore, in high strain-rate tension tests, the onset of necking seems to be a function of the loading rate (Fellows and Harding, 2001), and accurate local measurements of strain localisation are important in studies of dynamic ductile failure.

A vast amount of research has been carried out on localisation phenomena experimentally, theoretically, and numerically (Zener and Hollomon, 1944; Needleman and Tvergaard, 1983; Needleman, 1988; Noble et al., 1999; Wattrisse et al., 2001; Hopperstad et al., 2003; Kajberg and Lindkvist, 2004; Stepanov and Babutskii, 2005). In a quasi-static test, it is possible to measure the area reduction in the necked region continuously during deformation with mechanical equipment. However, this method is not suitable for high strain-rate tests. Hopperstad et al. (2003) studied the combined effects of strain-rate and stress triaxiality on the deformation behaviour of structural steel using optical measurements. Noble et al. (1999) monitored the nature of localisation at high strain-rates using high-speed photography and then comparisons were performed between the numerically predicted and experimentally observed specimen geometry. However, it is so far not possible to accurately measure the extent of localisation from high-speed images of the deformed specimen. It appears that the study of localisation of materials subjected to high strain-rates is still in the early stages due to lack of measurement techniques to obtain accurate field data in the localised region.

In order to obtain more meaningful measurements in the localised region, a robust full-field measurement method is required. Optical measurement methods including laser interferometry, speckle photography and image correlation methods provide promising alternatives. In particular, digital image correlation (DIC) has become popular for full-field measurements in problems related to solid mechanics (Sutton et al., 2000). The advantage of this method is its simplicity and that it sometimes avoids difficult interpretations of interferometric fringes (Hung and Voloshin, 2003). Accordingly, the method has been widely applied to different situations, such as studies of the strain localisation phenomena that occur during the tension of thin, flat steel samples, analysis of multi-axial behaviour of rubber-like materials, and microscopic examinations of the fracture processes in concrete (Chu et al., 1985; Choi and Shah, 1997; Wattrisse et al., 2001; Hild et al., 2002). However, digital image correlation (DIC) in conjunction with high-speed photography has not been used very often in high strain-rate tension tests. On the other hand, digital speckle photography has been used by some researchers in investigations of dynamic material behaviour (Grantham et al., 2003; Kajberg and Sjödahl, 2003; Kajberg et al., 2004; Kajberg and Wikman, 2007). One of the aims of the present paper is to assess the performance of DIC for high strain-rate tests.

The most widely used method for high strain-rate testing is the Split-Hopkinson bar method (Kolsky, 1949) due to its relative simplicity and robustness. Many recent developments have been achieved in its widespread usage from metals to polymers, round to flat specimens, conventional measurements to optical measurements (Verleysen and Degrieck, 2004). However, there are some inherent gripping artefacts associated with the testing of sheet metals (Huh et al., 2002) in the Split-Hopkinson bar. In order to avoid these problems, a new specimen design initiated by Albertini (2006) is proposed in this study and its validity has also been checked with respect to attaining dynamic equilibrium in the specimen during deformation.

In the subsequent numerical studies of dynamic processes it is necessary to adopt a constitutive law that accounts for strain-rate dependence. An elasto-viscoplastic constitutive relation was used in the present study to predict localisation of plastic deformation at high strain-rates.

The present paper aims at studying the localisation in a very ductile dual-phase high-strength steel under elevated strain-rates. Low to medium strain-rate tests were performed in a servo-hydraulic testing machine, while high strain-rate tests were conducted using a Split-Hopkinson Tension Bar (SHTB). Real-time measurements of strain and displacements were obtained at high strain-rates using high-speed photography in combination with digital image correlation. The material parameters in an elasto-viscoplastic constitutive model