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Strain rate measurements by speckle interferometry for necking investigation in stainless steel

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ABSTRACT

Localization that occurs at the end of the tensile test of a ductile 316L stainless steel has been followed in detail by in-plane Electronic Speckle Pattern Interferometry (ESPI). A global description of the whole strain-rate field with an analytical function and physical descriptors such as band width, band inclination and maximum strain rate is proposed. The description with two straight bands of constant amplitude along the width of the specimens is valid from the beginning of the diffuse necking to the fracture of the specimens. It allows distinguishing between two localization scenarii which occur for specimens with a different width to thickness ratio, one with a fracture inclined along the width and the other with a fracture inclined in the thickness. For the former, the two bands keep a constant angle while for the latter, the two bands rotate progressively until they become perpendicular to the tensile direction. The bandwidth can be defined and monitored during the whole necking evolution.

1. Introduction

Plastic strain localization phenomena, such as necking, Piobert–Lüders bands, Portevin–Le Châtelier effect, may cause significant problems in metalworking processes. Necking, in particular, occurs when the work-hardening rate decreases under a certain threshold and causes the plastic flow to become instable. The onset of necking is well referenced in the literature but relatively few studies are devoted to the evolution of the neck between the onset and the fracture of the specimens, especially from the experimental point of view.

The aim of the present paper is to introduce a high resolution method to:

- Monitor the evolution of the strain rate field during necking development.
- Extract from the data some global features such as band width, band amplitude and band inclination without reference to any theoretical or numerical model.

It will be shown that the complex pattern formed by the strain rate field can be described quantitatively as the mere addition of two bands with constant amplitude across the width of the specimen. Two examples are given on two specimens with different aspect ratio of the cross-section.

The recent development of photomechanical methods such as moiré interferometry, grid method, Digital/Electronic Speckle Pattern Interferometry (DSPI/ESPI), Digital Image Correlation (DIC), fringe projection or infrared thermography has triggered a series of experimental studies on strain localization phenomena. A brief review is given below.

Some pioneering work was performed by Toyooka and Gong (1995), Gong and Toyooka (1999), Suprapedi and Toyooka, 1997, Yoshida and co-workers (Yoshida et al., 1998, 1999; Yoshida, 2000) or Vial-Edwards and co-workers (Vial-Edwards et al., 2001) who used ESPI to observe heterogeneous strain patterns at various stages of a tensile test. However their exploitation of fringe patterns remained purely qualitative albeit correlated to the stress–strain curve of the specimen. Guelorget and co-workers (Guelorget et al., 2006) showed that ESPI was sensitive enough to detect the localization onset before the Considère criterion (Considère, 1885) of maximum force. In their work, ESPI fringes were exploited quantitatively to obtain the strain rate evolution during necking development. It was shown that necking corresponds to a sharp acceleration of the local strain rate. Indeed, the evolution of strain rate after the onset of necking is very similar to the evolution of the void fraction which was observed with microtomography by Maire and co-workers (Maire et al., 2008). This work was extended to the monitoring of strain rate by ESPI during bulge testing of metal sheets (Montay et al., 2007a,b; Wang and Liu, 2010). In specimens in which a nanocrystallized surface layer was created by severe plastic straining, it was shown, by following the strain rate by ESPI, that the thin hardened layer could

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start the onset of necking for smaller strains values but did not affect the neck development (Petit et al., 2011).

Matic and co-workers have used a direct video imaging of specimen shape to analyze the neck evolution (Matic et al., 1988). Geometrical moiré was used as early as 1966 by Theocaris and Marketos to obtain contour plots of sheets thicknesses during necking (Theocaris and Marketos, 1967). Diffuse and localized necking evolutions were followed by Cordero and co-workers in an aluminum 1100 specimen by moiré interferometry (Cordero et al., 2005) and in a brass specimen by fringe projection (Cordero et al., 2010). Chrysochoos and Louche used infrared thermography (Chrysochoos and Louche, 1998) in conjunction with DIC (Chrysochoos and Louche, 2000) to monitor the progressive localization of strain during the tensile test of a steel specimen. Although neutron diffraction is not stricto sensu a photomechanical method, it can be mentioned that Baczmanski and co-workers (Baczmanski et al., 2011) have used it to investigate the evolution of grain stresses and damage inside the neck of a tensile specimen of duplex stainless steel and showed a decrease of stress in the damaging ferrite phase.

Digital Image Correlation (DIC) is one of the most extensively used techniques to study plasticity and damage beyond strain localization in smooth or notched specimens. Wattrisse and co-workers have shown that necking is a progressive phenomenon and that strain rate is a relevant quantity to monitor its evolution (Wattrisse et al., 2001a,b). Several studies, devoted to the identification of constitutive behavior, used DIC, in conjunction with Finite Element Modeling, to get information in the localized area (Kajberg and Lindkvist, 2004; Coppieters et al., 2011; Kamaya and Kawakubo, 2011; Tardif and Kyriakides, 2012). Others works investigated some specificities of necking phenomenon: Dunand and Mohr (2010) have studied the influence of stress triaxiality on the strain to fracture for notched specimens and specimens with a hole while Ding and co-workers (Ding et al., 2013) have used DIC to analyze quantitatively the influence of the global strain rate on the onset of diffuse and localized necking of high strength steel. DIC was also used to experimentally identify damage evolution in the localized area (Wu et al., 2011).

The point of view developed in the present article is to extract directly some global features to describe the localization phenomena without using a priori a constitutive model of the material. A particular emphasis is put on the evolution of bands widths during necking development. Being model independent, the results of the present study can be used to validate local or non-local ductile damage models.

Indeed, very little work has been done, to specifically study the experimental evolution of the width of the localization zone during a mechanical test, with or without the help of a numerical model. Berthaud and co-workers used Acoustic Emission to determine the width of localization zones in concrete and found that it was about 5 times the largest size of heterogeneities (Berthaud et al., 1991). An internal length was also measured in concrete by Bažant and Pijaudier-Cabot with an indirect method which compares the global behavior of two specimens, one restrained to promote diffuse damage and the other not restrained to let damage localize (Bažant and Pijaudier-Cabot, 1989). It was found that it was about 3 times the largest size of heterogeneities. Belnoue and Korsunsky, 2012 implemented a finite element model using two parameters, the non-local radius and a mixture parameter between the local and the non-local strain, to calculate the width of the localization zone, which, in their case, does not evolve with strain. They used Digital Image Correlation to calibrate their model but not to actually follow the width. Guelorget and co-workers have used ESPI to analyze the progressive narrowing of the localization band and compared it to a topographic measurement (Guelorget et al., 2009). They also found that the width obtained by ESPI was about one order of magnitude larger than the width obtained from Young's modulus variations obtained by instrumented indentation and attributed to damage variations (Guelorget et al., 2007).

The width and the shape evolutions of the localization band can be controlled by the behavior of the material, in the framework of a non-local constitutive behavior (Niordson and Tvergaard, 2005), or by structural effects (Tvergaard, 1993; Okazawa, 2010). The authors of the present paper believe that a characterization through global parameters can help analyzing these phenomena, especially for structural effects. In the present paper an example is given for two specimens with different aspect ratios of their cross-section. It will be shown that their behavior can be followed and distinguished during necking thanks to phase-shifting ESPI and a global description of the displacement/strain field.

2. Electronic Speckle Pattern Interferometry (ESPI)

Electronic Speckle Pattern Interferometry (ESPI, also called Digital Speckle Pattern Interferometry DSPI) is a technique that is widely used to measure full-field deformation on surfaces of many kinds of objects (Jones and Wykes, 1989; Cloud, 1995; Jacquot, 2008). ESPI is a non-contacting displacement measurement method used on rough surfaces. The speckle interferometer used in this study is a classical two beams interferometer sensitive to in-plane displacements known as a Leendertz set-up. The sensitivity vector $\vec{s}$ is parallel to the tensile direction. It is defined by $\vec{s} = \vec{k}_1 - \vec{k}_2$, where $\vec{k}_1$ and $\vec{k}_2$ are the directing vectors of the two incoming beams (Fig. 1). The laser beam was separated into two beams by a beam-splitter and directed towards the specimen by mirrors, where they interfere. Between the mirrors and the specimen, each beam was expanded by a lens and filtered through a 15 μm diameter pinhole in order to cover the entire sample and get rid of high spatial frequencies. The speckle pattern is a seemingly random distribution of intensity arising from multiple interferences of the laser light on the microtopography (roughness) of the specimen surface. Due to the spatial coherency of the laser light, this pattern contains information on the position of the points of the surface through a quantity called the phase. A CCD camera (1280 pixels × 960 pixels, monochromatic, 8 bits) mounted with a

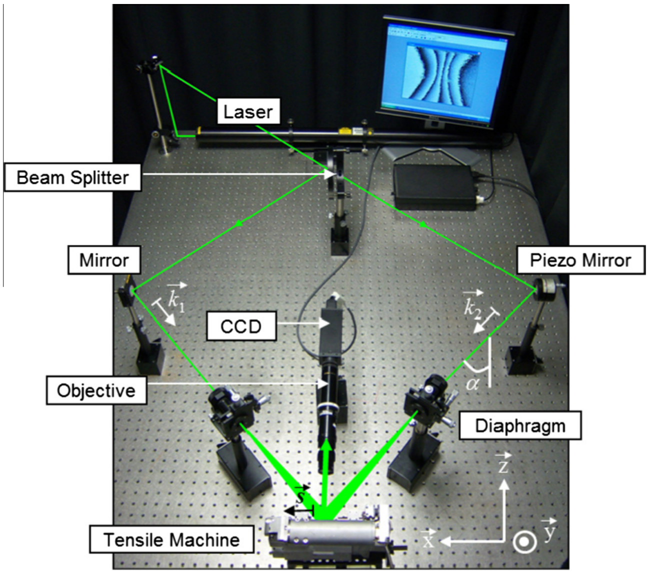

Fig. 1. Experimental setup: in-plane speckle interferometer and micro-tensile machine. The laser beam path is schematized as a green line. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)