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Strain rate distribution and localization band width evolution during tensile test

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ABSTRACT

The main objective of this paper is to study the evolution of the necking zone in a flat specimen during a tensile test. Two approaches are used and compared:

- An experimental investigation of the strain rate distribution with Electronic Speckle Pattern Interferometry (ESPI).
- A numerical analysis with a thermodynamically consistent constitutive model that couples strongly isotropic continuum damage (CDM) and the elastoplastic behavior.

It is shown that strain rate maps are, for both approaches, relevant to investigate the development of the X-shape pattern that occurs during necking evolution. In particular, this pattern can be clearly observed on maps of the minimum determinant of the acoustic tensor. It appears even when damage values are low and the problem is still elliptic.

It is shown that ESPI and CDM modeling are able to give a coherent picture of the phenomena that occur during neck development from the onset of instability to localize necking, in particular on localization bands angles and widths. In particular, physically meaningful information which is seldom considered such as band width evolution or strain rate distribution will be extracted from the analysis.

1. Introduction

The general idea of this paper is based on the analysis of the tensile test of a thin metallic sheet, in particular during the diffuse necking stage, up to the localize necking. When the behavior is homogeneous, it is rather simple to measure the strain distribution in the specimen by mechanical methods (strain gauge or extensometer) or by optical methods (photogrammetry or Digital Image Correlation). It becomes more complicated when a singularity, such as a neck or a crack, disturbs the metal behavior and creates heterogeneities in the strain field. During the necking of the specimen, softening phenomena such as damage, lead to instabilities which are reflected, on one hand in the numerical model through a mesh dependency and, on the other hand in the experiments through the strong strain velocity gradients that require high accuracy photomechanical methods.

Full field optical methods started to be used during the 90s to monitor mechanical tests and observe strains heterogeneities due to material behavior such as Lüders bands, Portevin–Le Chatelier effects or the development of necking. Toyooka and Gong (1995), Suprapedi (1997), Gong and Toyooka (1999), Vial-Edwards et al. (2001) and Zhang et al. (2005) have used Electronic Speckle Pattern Interferometry to follow the evolution of strain patterns during tensile tests. Yoshida et al. (1997), also using ESPI, followed rotation patterns and observed the appearance of a moving "white band" indicating strong strain localization. Wattrisse et al. (2001a,b) have used Digital Image Correlation (DIC) to investigate Lüders bands and necking behavior of steel specimens and have shown a considerable increase of the local strain rate in the neck as compared to the average strain rate. Zavattieri et al. (2009) have also used DIC for Portevin–Le Chatelier bands. Moiré interferometry was also successfully used by Cordero et al. (2005) to exploit quantitatively the displacement and rotation field to analyze the heterogeneities preceding localization. Using the high accuracy of ESPI technique, a series of studies were performed to follow quantitatively the development of necking phenomena through strain rate measurement in various configurations: tensile test (Guelorget et al., 2006a,b), hydraulic bulge test (Montay et al., 2007a,b; Wang and Liu, 2010), tensile test on a multilayer specimen with a nanocrystallized surface layer (Petit et al., 2011). It was then proposed to fit a Lorentz function to the strain rate distribution to extract the integral width of the localization zone and

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follow its decrease during a tensile test (Guelorget et al., 2009; Petit et al., 2013). Besides kinematic field measurements described above, it should be mentioned that infrared thermography is also able to provide valuable information on necking initiation and development (Chrysochoos and Louche, 2000).

Many papers propose different methods or models to predict the defects which may occur in a metal component when it is deformed by various forming processes. Formability of metallic parts means the capacity of the part to carry a large plastic "homogeneous" deformation without any strong localization, giving some through thickness (sheet or tube) necking prior to a macroscopic crack formation. In engineering practice, the material formability is usually assessed with strain-based (Marciniack et al., 1973) forming limit diagrams (FLD) in the case of linear (or proportional) strain loading paths. These forming limit diagrams or curves are determined from the experimental measurement of the necking or local fracture onset under linear strain paths using the minor and major principal strain diagram. However, it has been shown (Arrieux, 1995; Stoughton, 2001; Assempour et al., 2009; Chien et al., 2004) that these strain-based forming limit criteria are not efficient when the applied strain path is not linear (or is non-proportional). On the other hand, the prediction of plastic strain and its value at the final fracture is highly dependent on the used constitutive equations and whether or not they account for non-linear mixed isotropic and kinematic hardening as well as the ductile damage effect on plastic flow and hardening evolution.

Another way, proposed in many works in order to enhance the predictivity of the forming limit curves, consists in completing the yield function of von Mises or Hill types by an appropriate instability criterion based on the pioneering works by Rice (1976), Swift (1952), Bressan and Williams (1983) and Hill (1952). Most instability theories assume the existence of an initial imperfection with a given geometrical/material definition, leading to a high sensitivity to the size of such an assumed initial imperfection. In order to avoid this problem, many authors proposed to replace the initial imperfection by using an appropriate ductile damage theory, which allows catching naturally the instability conditions due to the damage initiation without assuming any initial imperfection (Needleman and Triantafyllidis, 1980; Chu and Needleman, 1980; Brunet and Morestin, 2001).

An alternative approach, proposed in recent years, to predict the localized neck prior to fracture in sheet metal forming, is the full coupling between the material behavior and the ductile damage. Two different kinds of damage theories are used: the Gurson's based damage theory (Gurson, 1977; Zhu et al., 1992; Gelin, 1990; Brunet et al., 1996; Lee et al., 1985) and the continuum damage mechanics (CDM) theory (Lemaitre, 1992; Lemaitre and Chaboche, 1985; Saanouni, 2012; Saanouni et al., 2011; Benallal et al., 1988; Badreddine et al., 2010; Brünig, 2003; Haddag et al., 2009). This kind of fully coupled approach accounts for the direct interactions (or strong coupling) between the inelastic flow, including different kinds of hardening and the ductile damage initiation, growth and coalescence. This full coupling allows a "natural" description of the strain localization modes based on the effect of the ductile damage evolution on other mechanical fields such as the strain or stress field. Hence, it provides a simple and helpful way to predict **where** and **when** the inelastic flow localizes due to the earliest stage of ductile damage initiation without reference to any initial imperfection. As it is based on the generalized thermodynamics of irreversible processes, this kind of approach leads to constitutive equations (for elasticity, plasticity, mixed hardening, damage, friction) with material parameters having a clear intrinsic character. The coupling between the thermomechanical behavior and degradation (damage) leads to softening models and generates inevitably a strong localization of the plastic flow in regions of finite size. A local formulation (classical) leads to the determination of the localization conditions by a stability analysis, but it is insufficient to obtain the characteristic dimensions (width) of such localization zones. Numerically this means a strong dependence of the post critical mechanical solution (after the Considère point) with respect to the mesh element size.

Several recent papers have proposed to use full field optical method coupled with finite element modeling (FEM) to identify the constitutive behavior of metal sheets. Kajberg and Lindkvist (2004), Belhabib et al. (2008) and Dunand and Mohr (2010) used simultaneously DIC and FEM to compare the strain field and identify power law hardening behavior in notched specimens up to the appearance of localization bands. Tardif and Kyriakides (2012) extended the results to anisotropic work hardening behavior. Coppieters et al. (2011) have used the DIC technique to identify the post-necking hardening behavior of sheet metal through a computation of internal and external work. In their work, softening due to damage was not taken into account. Broggiato et al. (2007) also used DIC to identify a model including damage softening. Celentano and Chaboche (2007) presents an experimental and numerical characterization of ductile damage evolution. During a tensile test, Celentano et al. performed some loading and unloading cycles to measure the Young modulus softening. They concluded that to extract damage occurring at macroscopic scale, it is necessary to take into account the necking phenomenon. This has been done using simultaneously optical measurements of the cross-section and of the local strain within the necking area. Lugo et al. (2011) use the acoustic emission technique to quantifying the microstructural damage evolution under tensile loading for an aluminium alloy, a digital image analysis is also combined to measure the microstructure evolution of the specimen. The link between damage and necking was investigated in different grain families of a duplex stainless steel with neutron diffraction by Baczmanski et al. (2011) and Panicaud et al. (2011) who showed that damage occurs first in ferrite phase during the necking stage.

The aim of the present paper is (i) to introduce strain rate measured by ESPI as a relevant physical quantity to investigate the localization behavior during a uniaxial tensile test up to localize necking, (ii) to simulate numerically this tensile test with a 3D FEM and an advanced elastoplastic behavior model strongly coupled with isotropic continuum damage, (iii) to compare the two approaches and to propose a method to compute the band width evolution, (iv) to show that it is sufficient to identify the constitutive behavior on the force–displacement curve in order to obtain a kinematic field evolution that is consistent with experimental observations

2. Experiments

2.1. Specimen and experimental set-up

The tensile test of a copper specimen is schematized in Fig. 1. The principal geometrical parameters are: useful length 30 mm, width 18 mm and thickness 0.8 mm.

The specimen was machined in the rolling direction of the Cu-DHP sheet (Deoxidised High residual Phosphorous), with an average grain size around 10–30 um.". It is then deformed until complete fracture to obtain the force vs. displacement curve given in Fig. 2. This curve is the only information used to identify the constitutive model of Section 3.

A speckle pattern interferometer is positioned in order to visualize the strain field of the specimen mounted on the tensile machine. During the tensile test, a camera takes pictures of the speckle pattern of the deformed specimen with a fixed frequency acquisition. Subtraction of successive images gives fringe patterns