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Damage in duplex steels studied at mesoscopic and macroscopic scales

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ABSTRACT

Different experimental approaches have been performed in order to extract damage at several scales. In this paper two experimental methods are treated. Neutron diffraction coupled with tensile test has been performed to study damage at mesoscopic scale. At macroscopic scale, classical tensile test has been used to extract damage effects, from material hardening evolution. Optical measurements and particular data treatment have been used in order to correct data for the necking phenomenon at large deformation, for each experimental method. Damage process in duplex steels has then been analysed at both macroscopic and mesoscopic scales using scale transition models. Eventually, investigations at those scales have been compared to understand correlation between mesoscopic and macroscopic behaviour of our material.

1. Introduction

Nowadays, it is possible to develop numerical simulation for manufacturing processes in finite transformation. In order to improve the predictivity of finite elements analysis (FEA), it is necessary to provide accurate constitutive models for mechanical behaviour. Such a methodology is now classical. The aim of the present work is to develop experimental techniques and data treatments to study damage mechanisms for metallic materials. Indeed, it is now well known that the coupling between damage and plasticity leads to an accurate description of ductile damage in metal forming (Saanouni et al., 2000; Saanouni and Hammi, 2000; Lemaitre and Chaboche, 2001; Chaboche et al., 2006). In this paper, we have studied the opportunity to measure the mechanical consequences of damage in duplex steels, at different scales. Therefore, two scales have been considered and a particular experimental approach has been performed. Neutron diffraction coupled with in situ tensile test has been used to study damage at mesoscopic scale. Classical tensile tests have also been used to obtain damage at macroscopic scale, from hardening evolution.

Firstly, diffraction methods for lattice strain measurements can provide useful information concerning the nature of grains behaviour during elastoplastic deformation. The advantage of diffraction methods is that measurements are performed selectively only for the crystallites contributing to the measured diffraction peak, i.e. for the grains having lattice orientations for which the Bragg condition is fulfilled (Greenough, 1949; Gloaguen et al., 2002a, 2002b). When several phases are present within a specimen, the measurements of separate diffraction peaks allow the investigation of each phase independently (Amos et al.,

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1994; Fitzpatrick et al., 1997; Fréour et al., 2002, 2003, 2005; Quinta Da Fonseca et al., 2006; Dakhlaoui et al., 2006). Moreover, comparison of diffraction data with self-consistent model is very convenient to study elastoplastic properties at mesoscopic and macroscopic scales. Analysis of experimental data using model predictions helps us to understand the physical phenomena which occur during sample deformation (Wierzbanowski et al., 1992; Fitzpatrick et al., 1997; Baczmanski et al., 2008). Besides, mesoscopic and macroscopic parameters of elastoplastic deformation can be then experimentally identified (Baczmański et al., 1999; Clausen et al., 1999).

Secondly, classical tensile loading is used to provide damage evolution at macroscopic scale (Cabezas and Celentano, 2004). Indeed, damage has been measured here from elastoplastic hardening evolution (Lemaitre and Chaboche, 2001; Hfaiedh, 2009). To extract damage occurring at macroscopic scale, it is necessary to take into account the necking phenomenon (Celentano and Chaboche, 2007). This has been done using simultaneously optical measurements for the cross-section and for the local strain within the necking area. Macroscopic models have been then used to compare with experimental results. Consequently, an inverse method has been applied to identify model parameters. Errors have been taken into account to analyse results from different macroscopic models. Eventually, we have obtained different damage curves depending from the data treatment considered and corresponding to different spatial parts of the sample.

In this paper, we present the experimental results from both techniques, and compare them in order to characterize damage evolution of duplex stainless steels (DSS) which is of obvious interest for industrial applications in highly corrosive process, such as chemical, petrochemical, off-shore, nuclear or paper industries and are yet frequently studied (Chehab et al., 2010; Hedström et al., 2010).

Further data treatments and calculations are based on approximations and corrections, listed below and detailed in the later parts of the text.

(1) Whatever the scale, the experimental data are fitted with elastoplastic models without taking account damage. Damage is so extracted from fitting/comparison process and is treated within the continuous damage mechanics (CDM).
(2) In calculations, the elastoplastic models take into account non-linear isotropic hardening and texture evolution. However, stress concentration and triaxiality of stains and stresses are neglected as discussed further.
(3) Necking effect has been corrected through optical measurements of sample cross-section. Grids are also used to measure local strain and a particular calibration was especially applied for diffraction results.

2. Material

The studied material is an austeno-ferritic stainless steel, containing approximately 50% austenite and 50% ferrite. It was obtained by continuous casting, and then hot rolled down to 15 mm sheet thickness. The sample was prepared from UR45 N steels which chemical composition is given in Table 1. The characteristic microstructure of this steel consists of austenitic islands elongated along the rolling direction and embedded in a ferritic matrix. EBSD method has shown that all crystallites of ferritic phase have almost the same orientation, while austenitic islands are divided into smaller grains with different orientations of the lattice (Baczmański and Braham, 2004; Dakhlaoui et al., 2006; Baczmański et al., 2008). The sample (designated as UR45 N) was annealed during 1000 h at a temperature of 400 °C and next cooled in ambient air. It is well known (Lacombe et al., 1990; Mateo et al., 1997; Park and Kwon, 2002) that, at this temperature of ageing (lower than 475 °C), the decomposition of ferrite by the mechanism of spinodal decomposition occurs. Transformations in ferrite are mainly decomposition of $\tilde{\alpha}/\tilde{\alpha}'$ (into Cr-poor $\tilde{\alpha}$ and Cr-rich $\tilde{\alpha}'$ domains) and precipitation of an intermetallic phase rich in Ni, Si and Mo (the G phase). The role of $\tilde{\alpha}'$ and the G phases in hardening and embrittlement of ferrite is widely discussed in the literature and the majority of authors (Marcinkowski et al., 1964; Lagneborg, 1967) agree that hardening is attributed essentially to the $\tilde{\alpha}'$ phase. Indeed, the coherence shift between the lattice parameters of $\tilde{\alpha}$ and $\tilde{\alpha}'$ phases introduces internal stresses reducing the dislocations mobility. The G particles have very small size (between 1 and 10 nm generally and up to 50 nm occasionally) and they precipitate, more or less uniformly, in the ferritic grains depending on the chemical composition of steels. The largest particles are formed preferentially in defects: the others are formed in the $\tilde{\alpha}/\tilde{\alpha}'$ and austenite/ferrite interfaces. Some microstructural transformations may be present in the austenitic phase but they do not change mechanical properties of the material.

3. Experimental methods at mesoscopic scale

3.1. Measurements by neutron diffraction

The ENGIN-X diffractometer (Santisteban et al., 2006) was used to measure interplanar spacings $\langle d\rangle_{\{hkl\}}$ using time-of-fly (TOF) neutron diffraction method at the ISIS spallation neutron source. The experimental setup consists of two detector banks which are centred on horizontal scattering angles of 2 = ±90° (Fig. 1). The detectors measure time-resolved spectra, each Bragg peak being produced by reflections from a different family of {*hkl*} planes.

The sample shown in Fig. 1 with an initial diameter of *8 mm*, having axis aligned along rolling direction (RD) was machined from UR45 N steels. The lattice strains were "in situ" measured during uniaxial tensile loading. The load axis was aligned horizontally at +45° to the incident beam,

Table 1
Chemical composition of duplex stainless steel: mass-percent.

	C	Mn	Cr	Ni	Mo	Cu	S	N
UR45 N	0.015	1.6	22.4	5.4	2.9	0.12	0.001	0.17