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Elastoplastic deformation and damage process in duplex stainless steels studied using synchrotron and neutron diffractions in comparison with a self-consistent model

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ABSTRACT

In situ time of flight neutron diffraction and X-ray synchrotron diffraction methods were applied to measure lattice strains in duplex steels during a tensile test. The experimental results were used to study slips on crystallographic planes and the mechanical effects of damage occurring during plastic deformation. For this purpose the prediction of an elastoplastic self-consistent model was compared with the experimental data. The used methodology allowed to determine the elastic limits and parameters describing work hardening in both phases of studied polycrystalline materials.

In the second part of this work the developed elastoplastic model was applied to study damage occurring in the ferritic phase. The theoretical results showed a significant reduction of stresses localized in the damaged phase (ferrite) and confirmed the evolution of the lattice strains measured in the ferritic and austenitic phases.

1. Introduction

Duplex stainless steels are two-phase materials composed of an alpha phase (ferrite) having a b.c.c. crystal structure and a gamma phase (austenite) exhibiting an f.c.c. structure. Both phases combine high corrosion resistance and high mechanical properties, i.e. the ferrite increases the value of yield stress, and the austenite provides a ductile behavior. Several studies of a cast duplex steel used in nuclear power plants have been published (Bugat et al., 2001; M'Cirdi et al., 2001). These steels are subjected to a slow thermal aging at the working temperature of 320 °C, which causes an embrittlement of the ferritic phase (Bonnet et al., 1990). As shown in the literature, the spinodal decomposition of ferrite into α (poor in Cr) and α' (rich in Cr) phases and the precipitation of G-phase (rich in Ni, Mo and Si) occur at temperatures lower than 475 °C (Park and Kwon, 2002). The presence of α' and G phases reduces mobility of dislocations and consequently cause hardening and embrittlement of the ferrite (Lagneborg, 1967). The G particles are very small (between 1 and 10 nm, and up to maximum 50 nm) and

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they are usually homogenously distributed in the ferritic grains. The largest particles are formed in defects as well as in the interfaces (α/α' and austenite/ferrite).

It is known that the plastic strains in this material are homogeneous in the austenitic phase and more localized in the ferritic phase, where less slips but with a higher magnitude are observed (El Bartali et al., 2010; Bugat et al., 2001). As SEM (Scanning Electron Microscopy) examinations for cyclic loadings has shown, the slip systems are first activated in the austenite, before slips in the ferrite (El Bartali et al., 2010). Due to the above described mechanisms, the damage in aged duplex stainless steel appears mainly in the ferrite. For instance, cleavage micro-cracks oriented perpendicularly to the direction of loading were shown by M'Cirdi et al. (2001) and Bugat et al. (2001). Moreover, M'Cirdi et al. (2001) used X-ray diffraction during an *in situ* tensile test to determine lattice strains and stress evolution in coarse-grained ferrite within a cast aged duplex steel. As a result, a significant decrease of the stress/strain perpendicular to {100} crystallographic planes was observed for this ferritic grain in which cleavage cracks appeared. Using electron microscopy (EBSD, TEM and SEM techniques) the initiation of cracks due to a cyclic loading was also seen in the ferritic phase (Balbi et al., 2009; El Bartali et al., 2008; Strubbia et al., 2014, Alvarez-Armas et al., 2012; Krupp et al., 2015). Recently, the electron microscopy studies were correlated with X-ray synchrotron diffraction and the effect of significant lattice strain release in damaged ferrite grains was confirmed by Istomin et al. (2014).

Most of the experimental works concerning damage in polycrystalline materials were based on a direct observation of cracks initiation and evolution using electron microscopy (e.g. Strubbia et al., 2014; Istomin et al., 2014; Krupp et al., 2015) or X-ray tomography (e.g. Maire et al., 2005; Bettaieb et al., 2011; Krupp et al., 2015). In the present work, an elastoplastic behavior of grains, as well as initiation of micro-damage during monotonic loading of a two-phase material (duplex steel) will be studied by diffraction methods and the experimental results will be interpreted using a multiscale elastoplastic model. Using diffraction the measurements of lattice strains can be performed selectively for the groups of crystallites contributing to the intensity of the scattered beam. In the case of multiphase materials the strains can be measured independently for each phase if the diffraction peaks are well separated (Inal et al., 1999; Daymond and Priesmeyer, 2002; Fréour et al., 2003; Baczmański and Braham, 2004; Dakhlaoui et al., 2006; Jia et al., 2009; Baczmański et al., 2011; Gloaguen et al., 2013; Francis et al., 2014). Although it is selective, diffraction enables sampling of a significant volume of the material (several hundred or many more crystallites for one peak and almost the whole irradiated volume when several scattering vector orientations are analyzed) and thus leads to statistically significant results.

The diffraction measurements performed *in situ* during tensile tests were usually compared with the Eshelby (1957) type models using a small deformation formalism (up to *ca*. 10% of sample strain). For instance, the self-consistent model developed for anisotropic polycrystals by Turner and Tomé (1994), was used for the interpretation of the diffraction measurements by Clausen et al. (1999), Daymond and Priesmeyer (2002), Francis et al. (2014) and Jia et al. (2008, 2009). This method was also applied by Neil et al. (2010) to study mechanical phenomena occurring at microscale in the polycrystalline copper and austenitic steel deformed up to *ca*. 30% of sample strain. In that work the rotations of the grain lattice was used to predict evolution of texture during plastic deformation and the model values of lattice elastic strains were successfully compared with diffraction results.

Another self-consistent elastoplastic model but also based on the Eshelby-type interaction was elaborated by Lipinski and Berveiller (1989). In the frame of this model the calculations can be done for arbitrary large strains and the rotation of the grain lattice is considered. More recently, this scale transition model was applied to study the influence of intragranular microstructure on ductility and forming limits in multiphase steels or single phase b.c.c. steel (Franz et al., 2014), and analysis of stress localization for polycrystalline material (Franz et al., 2013). The same model was also used for the interpretation of diffraction measurements performed for two-phase duplex steels (Baczmański and Braham, 2004; Baczmański et al., 2011; Wroński et al., 2007).

In the frame of Finite Element Analysis (FEA) the modeling of damage can be carried out in two ways. The first one is to introduce discrete elements corresponding to cracks or voids. The dynamic evolution of these discontinuities enables description of the different stages of damage evolution: germination, growth and coalescence. Such a description is adapted to ductile materials through a scalar variable describing the volume fraction evolution of those cracks or voids. Over the years several modified models have been proposed, taking anisotropy effects into account (Li et al., 2011; Bettaieb et al., 2011; Lecarme et al., 2011; Malcher et al., 2014, among others).

In the second approach, a continuum thermodynamics methodology is applied to obtain the so-called Continuum Damage Mechanics (CDM). In the CDM method the dissipation potentials and variables describing damage are derived in the frame of the thermodynamics. In this formulation damage is one of the internal constitutive variables describing the irreversible processes occurring in the material. The local CDM theory developed by Lemaitre and Chaboche (1978) assumed that the strain tensor and the damage parameter are defined at a given point of the continuum. To avoid strain localization at vanishing volume, the non-local continuum approach based on the concept of Representative Volume Element (RVE) was proposed (Pijaudier-Cabot and Bažant, 1987). The non-local damage models consist in replacing a certain variable by a mean value averaged over a spatial neighborhood of each considered point. Several modified models have been proposed in more recent years accounting for different effects in the frame non-local modeling (Marotti De Sciarra, 2012; Basirat et al., 2012; Brünig et al., 2015; Vignjevic et al., 2012; Balieu and Kringos, 2015; Nguyen et al., 2015; Dormieux and Kondo, 2015, among others).

The damage effect was also included into continuum models introducing additional information from the microscopic level of complex materials. The direct multiscale FEA calculations of the real microstructures are computationally expensive,