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Subgrain lath martensite mechanics: A numerical–experimental analysis

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ABSTRACT

Lath martensite reveals a specific hierarchical subgrain structure, with laths, blocks and packets of particular crystallography. The presence of interlath retained austenite layers has been reported in the literature. This paper investigates the potential influence of the interlath retained austenite on the mechanical behaviour of lath martensite subgrains. To this purpose, a martensite grain substructure is modelled using a crystal plasticity framework, with a BCC lath–FCC austenite bicrystal at the fine scale. The main novel contribution of this work is the validation of the hypothesis on the role of the interlath retained austenite in lath martensite using the experimental results reported in the literature. The main features of the experimentally observed deformation behaviour (stress–strain curve, slip activity and roughness pattern) are qualitatively well reproduced by the model. It is shown that the presence of austenite interlath films has the potential to remarkably enhance the local deformation of martensite. In spite of its minor volume fraction, it plays a major role in the orientation dependent mechanical behaviour of the aggregate. It is also shown that if the presence of interlath austenite is neglected, the observed experimental flow curves are not captured.

1. Introduction

The design of advanced high strength steels (AHSS), which are characterised by both good strength and formability, dates back to the early 1970s (see e.g. Rashid, 1981 for the case of Dual Phase steels). In the past decade, their development increased even further by a growing demand for light-weight vehicles and new safety standards.

Lath martensite is one of the main constituent phases in a number of AHSS, such as martensitic steels (Mine et al., 2013), Dual Phase (DP) steels (Cai et al., 1985; Steinbrunner et al., 1988; Calcagnotto et al., 2010) and other multi-phase steels (e.g. low alloyed TRIP steels (Jacques et al., 2007)). Beyond multiple applications in the automotive area, lath martensite is also used e.g. in MEMS (Mine et al., 2013). However, its mechanical behaviour still raises questions (Michiuchi et al., 2009).

Most modelling work on multiphase steels presented in the literature considers lath martensite as a hard, sometimes elastic isotropic phase (Sun et al., 2009; Uthaisangsuk et al., 2011). However, clear evidence exists of the strongly orientation dependent mechanical behaviour of martensite (Mine et al., 2013; Ghassemi-Armaki et al., 2013). Moreover, a number of papers (Cai et al., 1985; Steinbrunner et al., 1988; Calcagnotto et al., 2010; Ghadbeigi et al., 2010; Mine et al., 2013) report evidence of ductile deformation and fracture behaviour of lath martensite under uniaxial tension. This observation seems in

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contradiction with the commonly accepted low ductility of the BCC/BCT martensitic phase. Therefore, the following question arises: *what governs the lath martensite orientation dependent, apparently ductile behaviour?*

A deeper analysis of the lath martensite deformation mechanisms contributes to the further understanding of its damage and fracture behaviour, and may enhance the exploitation of its potential in technological applications.

To address this question, we depart from the current knowledge on the crystallography and morphology of lath martensite. Recent EBSD and TEM studies (Morito et al., 2003, 2006, 2011) have reported extensive evidence of the hierarchical crystalline substructure of low carbon lath martensite. During quenching from austenite, body centered cubic (BCC) laths form and group together according to a specific orientation relationship (approximately Kurdjumov–Sachs) with the parent austenite face centered cubic (FCC) lattice. The lath morphology and the crystallographic relation between multiple martensite subgrains can influence the local and overall anisotropic mechanical behaviour (Hatem and Zikry, 2009; Mine et al., 2013; Maresca et al., 2014). Also, since the martensitic transformation is never complete (Koistinen and Marburger, 1959; van Bohemen and Sietsma, 2009), thin interlath austenite films may be retained at lath boundaries. Their presence has been detected with TEM in lath martensite in a number of low carbon steels, e.g. martensitic (Law and Edmonds, 1980; Samuel, 1985; Morito et al., 2011), also tempered (Lee and Su, 1999), stainless steels (Nakagawa and Miyazaki, 1999), DP steels (Kim and Thomas, 1981; Rao and Sachdev, 1982; Jha and Mishra, 1999; Baltazar Hernandez et al., 2011; Kim et al., 2012), low alloyed TRIP steels (Nayak et al., 2012; Song et al., 2012).

We have recently shown (Maresca et al., 2014) that, provided there are enough carriers for plasticity, even a small fraction (5%) of FCC interlath retained austenite can influence the orientation dependent mechanical behaviour of lath martensite at the level of laths with approximately the same orientation. In particular, when shear is applied parallel to the BCC–FCC interface, localised plastic slip occurs in interlath austenite, leading to a remarkable increase of the overall deformation for a given stress level. This result is not just a mere consequence of the fact that the critical resolved shear stress (CRSS) of the FCC phase is lower than that of the BCC phase, but it is intrinsically related to the γ austenite - α' martensite orientation relationship, which is characterised by a habit plane of the approximately $\{111\}_\gamma$ family. Hence, there are always 3 slip systems in the FCC phase which are parallel to the BCC–FCC interface, i.e. they are most favourably oriented for carrying plastic slip along the interface.

So far, there was no direct experimental evidence of the role played by interlath retained austenite on the orientation dependent mechanical behaviour of lath martensite. The recent work of Mine et al. (2013) is here used to assess the possible role played by the interlath retained austenite in the mechanical behaviour of lath martensite. In Mine et al. (2013), micrometer-sized tensile specimens were fabricated from a fully lath martensitic low carbon, low alloyed steel. The crystallography of the specimens was identified by means of EBSD before performing mechanical tests. The specimens were strained up to fracture under quasi-static conditions, at room temperature. Stress–strain curves were calculated and surface undulations were measured by scanning white-light interferometry for some strain levels. It is shown that, in all cases, lath martensite does not loose ductility. Moreover, it is observed that slip occurs along lath habit planes at critical resolved shear stresses (310–360 MPa) that are lower than those related to the $\{112\}_{\alpha'}$ slip family in BCC laths (500–560 MPa). Slip systems parallel to lath habit planes, also named "in-lath-plane" slip systems are identified in Mine et al. (2013) with slip family $\{110\}_{\alpha'}$ of BCC laths. This is a commonly accepted view (e.g. Schastlivtsev et al., 1999) which attributes to lath martensite two "pseudo-single crystal" slip families, close to $\{110\}_{\alpha'}$ and $\{112\}_{\alpha'}$, that can activate in a BCC lattice. In this view, also referred to in Mine et al. (2013), the presence and the potential role of interlath retained austenite is ignored.

However, the strong difference in CRSS observed in Mine et al. (2013) may be due to the presence and activity of two different phases in lath martensite: BCC laths with FCC interlath retained austenite. The latter is known to be much weaker than highly dislocated BCC phase. Furthermore, some fractography views reported in Mine et al. (2013) (cf. Fig. 9d in Mine et al., 2013) suggest that ductile shear fracture can occur when lath habit planes are oriented ca. 45° with respect to the tensile axis, i.e. when shear occurs along the BCC–FCC interface. This observation is consistent with Maresca et al. (2014), and therefore calls for an in-depth analysis. Indeed, Maresca et al. (2014) lacks an experimental validation, which is provided here.

This paper aims to assess, based on the experimental results of Mine et al. (2013), the hypothesis proposed in Maresca et al. (2014). We investigate the role played by the hierarchical crystallographic structure of martensite, combined with the presence of very thin interlath austenite films, on the orientation dependent mechanical behaviour of lath martensite, as indicated by the experiments of Mine et al. (2013). To this purpose, a computational framework at the scale of martensite subgrains has been developed, incorporating the mechanical behaviour of martensitic laths through an underlying lamella model. At the scale of the lamella model, the crystallography of the BCC lath and FCC interlath retained austenite is included and modelled using a crystal plasticity approach (Bronkhorst et al., 1992). This two-scale model is used to simulate the deformation behaviour of two martensitic samples of different crystallography, as presented in Mine et al. (2013). The comparison of the simulation results with the experimental data (Mine et al., 2013) reveals the possible contribution of the interlath retained austenite to the deformation behaviour of lath martensite.

The paper is organised as follows. First, in Section 2 a brief summary is given of the existing experimental evidence on the morphology and crystallography of lath martensite and interlath retained austenite. Then, the modelling approach and the model setup are presented in Section 3 and 4, respectively. In Section 5 simulation results are presented and confronted with the experiments by Mine et al. (2013). The paper ends with a discussion and conclusions.

As stated above, lath martensite is in general a mixture of BCC laths and FCC retained austenite films. However, the presence of FCC films is usually neglected. It is shown that by accounting for the presence of BCC and a small volume fraction