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On the mechanism of twin formation in Fe–Mn–C TWIP steels

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Abstract

Although it is well known that Fe–Mn–C TWIP steels exhibit high work-hardening rates, the elementary twinning mechanisms controlling the plastic deformation of these steels have still not been characterized. The aim of the present study is to analyse the extended defects related to the twinning occurrence using transmission electron microscopy. Based on these observations, the very early stage of twin nucleation can be attributed to the pole mechanism with deviation proposed by Cohen and Weertman or to the model of Miura, Takamura and Narita, while the twin growth is controlled by the pole mechanism proposed by Venables. High densities of sessile Frank dislocations are observed within the twins at the early stage of deformation, which can affect the growth and the stability of the twins, but also the strength of these twins and their interactions with the gliding dislocations present in the matrix. This experimental evidence is discussed and compared to recent results in order to relate the defects analysis to the macroscopic behaviour of this category of material.

Keywords: TWIP steels; Dislocations; Twinning mechanisms; Transmission electron microscopy

1. Introduction

Even though Hadfield steel is one of the oldest modern steel grades, named after the work of Hadfield [1], there is currently a renewed interest in the huge work-hardening rate exhibited by Fe–Mn–C-based alloys that could find roles in new specific structural applications, e.g. in the automotive industry. The current acronym used to define these steels, TWIP, refers to the occurrence of mechanical twinning as a plastic deformation mechanism (twinning-induced plasticity). However, despite several decades of research, the real origin of the large work-hardening rate exhibited by these steels remains partially unclear. Two kinds of explanation currently exist in the literature.

According to Dastur and Leslie [2], the primary source of enhancement of the work-hardening rate of the Hadfield steels is a dynamic strain-aging mechanism. It is true that Fe–Mn–C, Hadfield-related, steels exhibit a serrated flow and a slightly negative strain-rate sensitivity, but no accelerated occurrence of necking. Dastur and Leslie argued that due to a strong interaction of solute atom dipoles (C–Mn) with the strain field of dislocations, these dislocations are pinned and locked, increasing the dislocation density and thus the work-hardening rate. Macroscopic measurements such as the rate of dislocation accumulation recently carried out by Hutchinson and Ridley [3] support this kind of influence on the work-hardening rate.

On the other hand, several authors have directly related the particular mechanical behaviour of these steels to the mechanically induced formation of twins. It is indeed an obvious fact that thin lamellae presenting a twin relationship with the initial austenite grain orientation appear during straining. Furthermore, it is worth mentioning that the morphology of the mechanical twins formed in TWIP steels is rather different from the ones formed in hexagonal close-packed metals such as Mg [4] or Ti [5].

For Raghavan et al. [6], and more recently Bouaziz and Guelton [7], the thin twin lamella that progressively form with increasing strain subdivide the original grains, thus

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reducing the dislocation mean free path and improving the work-hardening rate through a "dynamic Hall–Petch" effect. In order to explain the huge level of back-stress (up to half of the total stress) that appears with strain in these steels, Bouaziz et al. [8] then complemented their approach by modelling the kinematic hardening resulting from the dislocation pile-ups at the twin boundaries. Finally, Gil Sevillano [9] also proposed a new explanation based on mechanical arguments and more focused on the reinforcement of austenite by thin (nanometer thick) deformation twins.

Beside these different explanations, experimental evidence is sometimes missing, particularly at the scale at which the plasticity mechanisms are active, i.e. at the dislocation scale. Indeed, since the work-hardening rate is directly related to the plastic relaxation mechanisms, i.e. the creation, interactions and annihilation of dislocations, it is of primary importance to accurately consider the dislocations present in Fe–Mn–C TWIP steels. The present study thus aims at understanding the source of the huge work-hardening rate exhibited by the Hadfield-related Fe–Mn–C TWIP steels thanks to a complete and accurate characterization of the twinning growth mechanism and the interactions between dislocations and twins.

2. Mechanisms of twin formation in face-centred cubic (fcc) metals

Several fundamental mechanisms for mechanical twinning in fcc materials have been proposed in the literature, though without obtaining unanimity due the heterogeneous character of the observations (different materials and different deformation conditions). These mechanisms can be categorized into three main groups depending on the characteristics of the dissociation process of the $b = \frac{a}{2}\langle 110\rangle$-type glide dislocation.

2.1. Pole mechanism

According to this model proposed by Venables [10], prismatic glide sources could dissociate under the action of a stress into a Frank partial dislocation (pole dislocation) of type $\frac{a}{3}\langle 111\rangle$ and a Shockley twinning partial of type $\frac{a}{6}\langle \bar{2}11\rangle$. The created Shockley partial moves away from the sessile Frank partial, leaving a wide intrinsic stacking fault (SF) behind it. When attaining the unstable semicircular configuration, the Shockley partial winds down to the underlying close-packed plane, where it recombines. If this process is repeated on every plane, a twin structure is formed. In this case, very particular dislocation configurations and dislocation dissociation processes, which are energetically unfavourable, are needed. Furthermore, this process cannot explain the high rate with which the twinning phenomenon proceeds [11,12]. Hirth [13] proposed other pole dislocations of type $\frac{a}{6}\langle 411\rangle$ and $\frac{a}{3}\langle 221\rangle$, with a similar kind of pole mechanism.

In addition to this nucleation mechanism, Venables [33] proposed another mechanism to explain twin growth in fcc material. He suggested that Shockley partial dislocations in the twinning plane can react during their movement with perfect dislocations in the matrix and form several Frank dislocations lying at the interface plane, and considered as "secondary polar sources", according the equation:

$$\frac{a}{2}[\bar{1}0\bar{1}]_{(11\bar{1})} + \frac{a}{6}[121]_{(1\bar{1}1)} \rightarrow \frac{a}{3}[\bar{1}1\bar{1}]_{sessile}. \quad (1)$$

Venables [33] argued that these reactions represent the most efficient way of hindering the twin propagation of twin boundaries. It can also explain the stability of the twins after unloading.

2.2. Models based on a deviation process

Cohen and Weertman [11] considered the dissociation of a perfect dislocation into a sessile Frank partial screw dislocation and a glissile Shockley partial when meeting a Lomer–Cottrell barrier. The equation of this dissociation is:

$$\frac{a}{2}[101]_{(1\bar{1}\bar{1})} \rightarrow \frac{a}{3}[1\bar{1}1]_{sessile} + \frac{a}{6}[121]_{(1\bar{1}1)}. \quad (2)$$

In this case, the deformation twinning occurs in the conjugate plane. One sessile Frank partial is created for each Shockley partial emitted.

On the other hand, Mori and Fujita [14] proposed the stair-rod cross-slip mechanism which consists of the dissociation of a Shockley partial dislocation gliding in the primary glide plane into a stair-rod sessile dislocation at the intersection of the primary and conjugate planes and an emitted Shockley partial in the conjugate plane following the equation:

$$\frac{a}{6}[\bar{2}11]_{(111)} \rightarrow \frac{a}{6}[\bar{1}\bar{1}0]_{sessile} + \frac{a}{6}[\bar{1}21]_{(\bar{1}\bar{1}1)}. \quad (3)$$

The authors provided experimental results supporting their model by observing the dislocation substructure of wide overlapping SFs on a conjugate twinning plane in deformed Cu–11 at.% Al single crystals.

For both models, multiple glide and high stress concentrations are needed to obtain dislocation dissociation in the twinning plane.

2.3. Models based on the presence of an extrinsic stacking fault

Mahajan and Chin [15] proposed the dissociation of two co-planar perfect dislocations into three Shockley partial dislocations on three consecutive adjacent close-packed planes, resulting in an extrinsic stacking fault configuration that acts as a three-layer nucleus for twinning. A macroscopic twin may evolve when these three layer nuclei, distributed at different levels within the locally slipped region, grow into each other. For example, the reaction in the $(1\bar{1}1)$ close-packed plane is:

$$\frac{a}{2}[011]_{(1\bar{1}1)} + \frac{a}{2}[\bar{1}01]_{(1\bar{1}1)} \rightarrow 3 \times \frac{a}{6}[\bar{1}12]_{(1\bar{1}1)}. \quad (4)$$