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On the strain hardening and texture evolution in high manganese steels: Experiments and numerical investigation ☆

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ABSTRACT

We present a systematic investigation on the strain hardening and texture evolution in high manganese steels where twinning induced plasticity (TWIP) plays a significant role for the materials' plastic deformation. Motivated by the stress–strain behavior of typical TWIP steels with compositions of Fe, Mn, and C, we develop a mechanistic model to explain the strain-hardening in crystals where deformation twinning dominates the plastic deformation. The classical single crystal plasticity model accounting for both dislocation slip and deformation twinning are then employed to simulate the plastic deformation in polycrystalline TWIP steels. While only deformation twinning is activated for plasticity, the simulations with samples composed of voronoi grains cannot fully capture the texture evolution of the TWIP steel. By including both twinning deformation and dislocation slip, the model is able to capture both the stress–strain behaviors and the texture evolution in Fe–Mn–C TWIP steel in different boundary-value problems. Further analysis on the strain contributions by both mechanisms suggests that deformation twinning plays the dominant role at the initial stage of plasticity in TWIP steels, and dislocation slip becomes increasingly important at large strains.

1. Introduction

The high ultimate strength, combined with a high hardening modulus to resist deformation localization in the twinning induced plasticity (TWIP) steels, stimulate broad interests from both academic society and industries. For example, Fe–Mn–Si–Al and Fe–Mn–C austenitic TWIP steels have been proposed to many applications (Grässel et al., 2000) where high strength and/or light weight materials are desired for lower energy consumption and further enhancement in safety, which is of paramount importance in the automotive industry (Liu et al., 2012). For example, the ultimate strength over density ratio of TWIP steels is comparable to that of nanocrystalline magnesium (Wei and Anand, 2007). Typically, the 0.2% yield strengths of TWIP steels are in the range of 350–500 MPa, which are at the same level of several conventional high strength steels including dual-phase (DP) steels and transformation-induced plasticity (TRIP) steels (Bouaziz et al., 2011a, 2011b; Krauss, 1990; Yoo et al., 2009; Zavattieri et al., 2009). Following the initial yielding, TWIP steels harden at a nearly constant

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modulus on the order of 1 GPa (Allain et al., 2008; Bouaziz, 2012; Bouaziz et al., 2010, 2008; Bouaziz and Guelton, 2001; Chen et al., 2007; Ding et al., 2011; Idrissi et al., 2010b; Jin and Lee, 2009; Liang et al., 2009; Sevillano, 2009; Shiekhelsouk et al., 2009). Due to the high strain hardening, TWIP steels can attain an elongation about 60–95%, and the corresponding ultimate strength is about 800 MPa to 1.8 GPa (Allain, 2002; Allain et al., 2002; Bayraktar et al., 2004; Chen et al., 2007; Dastur and Leslie, 1981; Frommeyer et al., 2003; Grässel et al., 2000; Huang et al., 2006; Kim et al., 2009; Lai and Wan, 1989; Mi et al., 2005, 2012; Vercammen, 2004). The diagram given in Fig. 1 summarizes the mechanics properties of several steels and other metallic materials of current interest, among which TWIP steels owe the most promising combination of strength and deformability.

The attractive properties in TWIP steels are attributed to the activation of twinning during their plastic deformation. At room temperature, deformation twinning is not regarded as the primary plastic carrier in conventional face centered cubic (FCC) metals because their stacking fault energy (SFE) is relatively high. It is reported that low intrinsic stacking fault energy γ_{sf} (below approximately 20 mJ/m^2) favors the γ (FCC phase) to ε (hexagonal close-packed, HCP phase) transformation in TWIP steels; while $\gamma_{sf} > 20$ mJ/m^2, this phase transformation is rarely observed (Sato et al., 1989). When γ_{sf} is too high, motion of complete dislocations takes over and becomes the primary plastic deformation mechanism. Such a transition can be readily explained if the nucleation of $a/6\langle 112\rangle$ Shockley partial dislocations and $a/2\langle 110\rangle$ complete dislocations are the controlling factors for the competition between deformation twinning and dislocation glide. The critical resolved shear stress (CRSS) τ_{crss} for the nucleation of an $a/6\langle 112\rangle$ Shockley partial dislocation is about $\tau_{crss}=\gamma_{sf}/b+\alpha Gb/3d$ (Asaro et al., 2003; Asaro and Suresh, 2005; Wei et al., 2006; Zhu et al., 2005), while the CRSS τ_{crss} for the nucleation of a complete dislocation approximates to $\beta Gb/d$, where b is the Burgers vector, G is the shear modulus, d is the grain size, and α and β are coefficients on the order of unit. The expressions for τ_{crss} indicate that materials with higher SFE tend to nucleate complete dislocations. That is to say, the SFE of FCC austenite needs to be in the right range, neither too low nor two high, in order to promote deformation twinning while the material is deforming at a certain range of temperatures and strain rates. Current understanding on the roles of manganese and carbon (or its alternatives) in TWIP steel enables us to tune the composition of the materials and achieve the suitable SFE to promote deformation twinning (Allain et al., 2010; Brüx et al., 2002; Curtze and Kuokkala, 2010; Curtze et al., 2011; Dumay et al., 2008; Idrissi et al., 2010a, 2009; Jeong et al., 2012; Jin and Lee, 2012; Lee et al., 2010; Park et al., 2010; Saeed-Akbari et al., 2011; Wang et al., 2010; Yoo and Park, 2008). It is worth pointing out that appropriate SFE is necessary but by no means a sufficient condition for twinning (Bouaziz et al., 2011a; Meyers et al., 2001). As commented by Christian and Mahajan (1995), loading modes, temperature, residual strain, grain size, and strain-rate all influence the activation of deformation twinning.

From the crystallographic aspect, motion of a complete dislocation gives rise to shear displacement of a portion of the crystal over another and leaves the lattice virtually unchanged. In contrast, shear displacement induced by a Shockley partial dislocation is only a fraction of the inter-atomic spacing. During twinning, the nucleation and gliding of several leading partials in successive planes result in mirror image lattice reorientations across the boundary. Now in addition to the initial crystallographic texture characteristics of TWIP steels resulted from rolling processing, deformation twinning further alters the texture dramatically. The reorientation induced by twinning brings exceptional yet unique characteristics in crystalline materials. For example, it is evident that the consequently formed mirror planes are effective barriers to dislocation slips inclined to those planes (Li et al., 2010). It hence enhances the strength of the material as deformation proceeds. As a result,

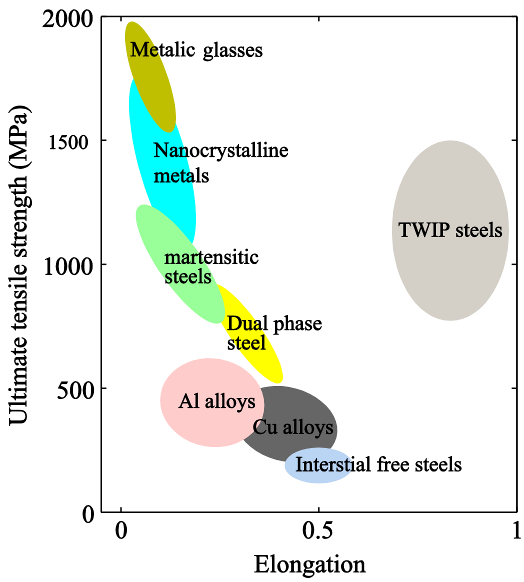

Fig. 1. Illustration to show the ultimate tensile strength versus elongation for several conventional metals, as well as metallic glasses and nanocrystalline metals. TWIP steels owe both high strength and large tensile elongation.