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Criteria for predicting twin-induced plasticity in solid solution copper alloys

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A B S T R A C T

The deformation-mode transition model was extended to predict wavy to planar-slip and subsequent twin-induced plasticity (TWIP) transitions in solid solution copper alloys. In the deformation-mode map, the stacking fault energy (γ/G) vs. frictional-stress ($2F_f$/G) curves for Cu-Al, Cu-Mn, and Cu-Zn, crossed the boundaries of wavy-slip to planar-slip and planar-slip to TWIP transitions, with an increase in the solute content. The critical solute content predicted for the transition from wavy-slip to planar-slip to TWIP, by the deformation-mode transition model, was in good agreement with observations for solid solution copper alloys. Excellent agreement between the predictions and experimental data in the literature suggested that TWIP in Cu alloys is enhanced not only by the low stacking fault energy, but also by the frictional-stress on twinning partial-dislocations.

1. Introduction

The strength–ductility trade-off has long been the rule in designing structural metals and alloys. The compromise between strength and ductility is still an important issue for the selection and design of processing, and has limited the potential applications of many structural alloys. Twin-induced plasticity (TWIP) and strengthening, due to the interaction between deformation-twins and dislocations, have rendered the development of high performance steels [1–3] that defy the conventional strength-ductility trade-off. The synergistic effects of deformation-twins and dislocations have provided a new design strategy for modification of the composition, processing, and microstructure of structural metals and alloys. The simultaneous enhancement of ductility and strength in TWIP steels is attributed to the high work-hardening rate associated with multiplicative interactions between deformation-twins and dislocations [4]. The increase in strength due to dislocation-twin interaction is described as the dynamic Hall-Petch effect [5,6], since the increasing population of deformation-twins with strain has an effect similar to that of grain-size refinement.

Recently, Liu et al. [7] reported a simultaneous increase in the strength and plasticity of Cu-Al alloys, termed “TWIP copper alloys”, following the concept of TWIP steels. The constructive interaction between deformation-twins and dislocations in TWIP copper alloys was found to lead to the improvement of both strength and plasticity [7,8], as in TWIP steels. TWIP copper alloys are primarily binary solid solution alloys, and the effects of stacking fault energy (SFE) and alloying elements on deformation-twinning and dislocation motion, are less complicated than in TWIP steels. In the present study, the deformation-mode transition model of Hong and Laird [9] was extended to predict the transition from wavy to planar-slip, and subsequently to TWIP behavior in copper alloys. The criteria for TWIP prediction may provide useful insights into designing high-performance engineering materials.

2. TWIP in solid solution Cu alloys

Deformation-twins (DTs) have been observed in various Cu alloys such as Cu-Al [7], Cu-Mn [8], and Cu-Zn [9]. Liu et al. [7] reported that deformation-twinning is a dominant mechanism in Cu-Al alloys with high Al content, exhibiting synchronous improvement in strength and plasticity (SISP), as in TWIP steels [1–3]. The stress-strain responses of pure Cu and Cu-Al alloys reported by Liu et al. [7], are summarized in Fig. 1. The thick red arrow in Fig. 1(a) indicates the direction of simultaneous improvement in strength and plasticity observed in these alloys. In Fig. 1(b), the increase in the ultimate tensile strength (UTS) with uniform elongation is more rapid than that of the yield strength (YS), reflecting the contribution of deformation-twinning during plastic deformation [7].

Enhanced ductility, along with an increase in strain-hardening was also observed in Cu-Mn alloys [8], similar to TWIP steels [1–3], TWIP Cu-Al alloys [7], and Cu-Zn alloys [9]. Fig. 2(a) and (b) show the engineering stress-strain curves and true stress-logarithmic strain curves of pure Cu and Cu-Mn alloys, reported by Han et al. [8] (the term “logarithmic strain” instead of “true strain” will be used, for accuracy from a mechanical point of view). The dashed red arrow in Fig. 2(a) indicates the direction of simultaneous improvement in strength and plasticity in Cu-Mn alloys. The SISP in Cu-Al alloys was attributed to the change in slip-mode and increased density of deformation-twins, associated with the decrease in the SFE. Han et al. [8] recently reported that

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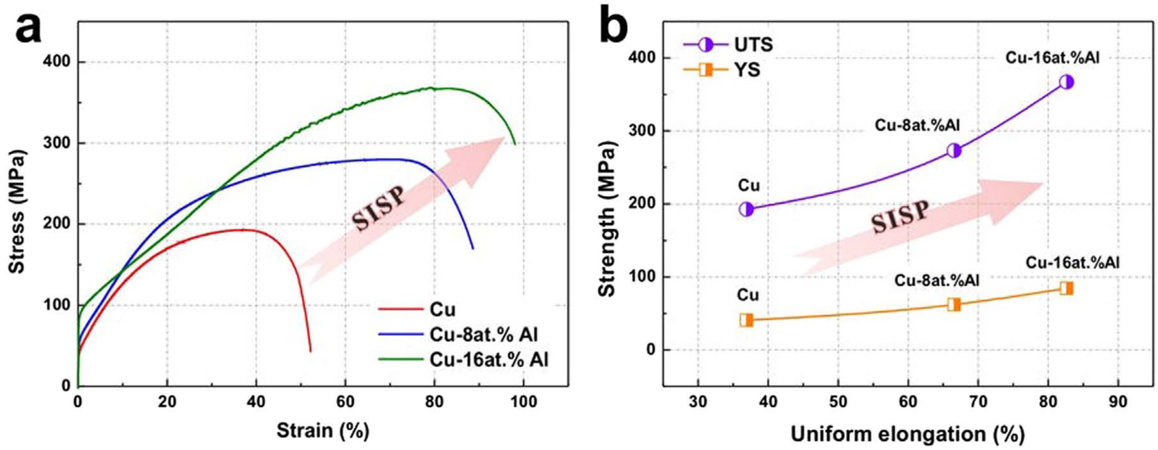

Fig. 1. (a) Engineering stress-strain curves of Cu and Cu-al alloys; (b) Plot of ultimate tensile strength (UTS) and yield strength (YS) against the uniform elongation. Permission granted from Nature [7].

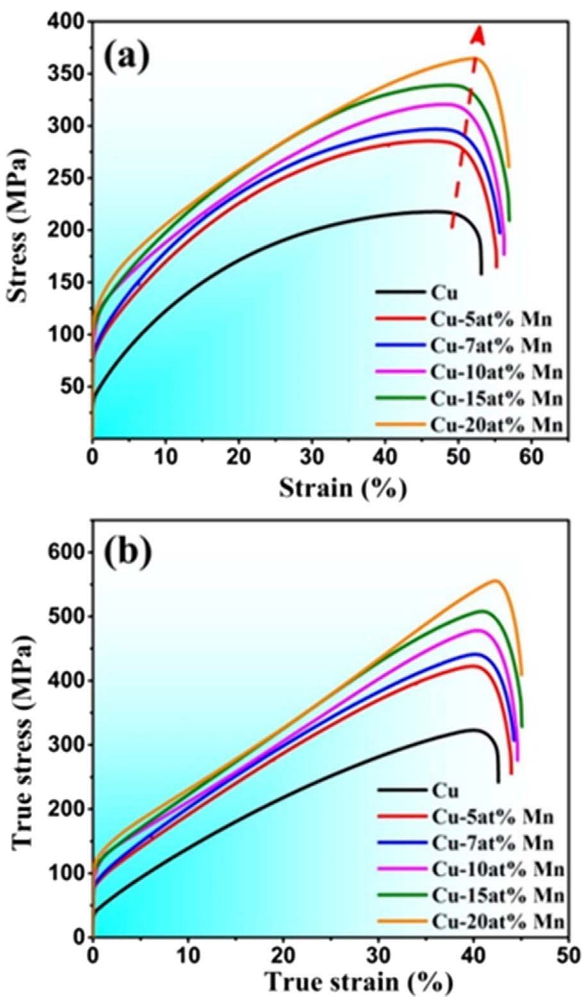

Fig. 2. (a) Engineering stress–strain curves of Cu and Cu-Mn alloys.; (b) true stress–logarithmic strain curves Cu and Cu-Mn alloys. Permission granted from Elsevier [8].

the deformed microstructures of Cu-Mn alloys with higher SFEs (close to that of pure Cu), exhibit dislocation-cells to planar-slip structures, followed by deformation-twinning, as the Mn content increases from 5 to 20 at%. The interaction between deformation-twins and dislocation-slip enhances the strain-hardenability, causing an improved strength-ductility match in Cu-Mn alloys.

The transitions in the deformation-mode of Cu-Mn alloys, along with the relevant deformation microstructures schematically depicted based on extensive mechanical testing and microstructural analyses by Han et al. [8], are displayed in Fig. 3. Han et al. [8] noted that deformation-twins are formed at the uniform deformation stage for both, Cu-15 at% Mn, and Cu-20 at% Mn alloys. They suggested that the enhanced deformation-twining in Cu-15 at% Mn and Cu-20 at% Mn alloys, can improve the strength [8] by increasing the work-hardening rate through the effect of TWIP, and thereby further enhance the ductility. The observation of planar-slip and deformation-twins in Cu-Mn alloys [8] cannot be explained in terms of their high SFE, because wavy-slip is favored with an increase in the SFE. Han et al. [8] proposed instead, that the SISP of Cu-Mn alloys can be attributed to the increasing degree of short range order (SRO), with increasing Mn content.

Numerous research groups [8,10–12] have attempted to explain the planar-slip mode observed in alloys with high SFEs, taking into consideration the effects of solute atoms. Gerold and Karnthaler [12], and Han et al. [8], suggested the role of SRO in promoting planar-slip. Wang et al. [11] proposed that the electron-atom ratio is more important than the SFE in promoting planar-slip. Although these models [11,12] predict the planar-slip behavior of alloys qualitatively, they lack the quantitative predictions of wavy-slip to planar-slip, and TWIP transitions.

3. Extension of deformation-mode transition model

Hong and Laird [10] suggested that two partial-dislocations separated by a stacking fault (SF), must overcome the repulsive force (F_R) between them, as well as the frictional-stress (F_f) imposed by segregated solute atoms at the partials [10] for cross-slip, and subsequent exhibition of wavy-slip behavior. They proposed a model to predict the wavy-slip to planar-slip transition quantitatively, with the assumption that the total force (F_T) needed to join two partial-dislocations in alloys, can be expressed as $\boldsymbol{F_T/G = \gamma/G - F_R/G - 2F_f/G}$. Here, γ is the SFE and G is the shear modulus. All forces here are those imposed per unit length of dislocations (N/m). The repulsive stress (N/m) can be defined as $F_R = G\,(b_1 \times b_2)/2\pi d$ (where G is the shear modulus in the units of N/m^2), b_1 and b_2 are Burgers vectors (in the unit of length) of partial dislocations and "d" is the separation (in the unit of length) between partials. Therefore, F_R also has the units of N/m. F_T represents the total force needed to be overcome, to join the partials. All terms in this equation, F_T/G, γ/G, F_R/G, and F_f/G have the dimension of length. Since the twinnability increases with stacking fault probability [13], the deformation transition model to predict the planar slip mode [10] induced by extensive stacking faults can be extended to predict the TWIP transition.

In Fig. 4, the balance of these forces between separate partial-