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Non-twinning deformation mechanism of pure copper under high speed electromagnetic forming

Huawen Jiang [a], Ning Li [a,*], Zhu Xu [a], Cong Yan [a], Duzhen Wang [a], Xiaotao Han [b]

[a] State Key Lab of Materials Processing, Die & Mould technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Wuhan National High Magnetic Field Center and State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, China

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ABSTRACT

The conventional high strain rate forming usually induces the occurrence of deformation twins in face-centered-cubic metals such as copper with medium stacking fault energy. In order to investigate the possible mechanical twinning of copper under a new type of high speed processing technique—electromagnetic forming, the pure copper was electromagnetically bulged followed by microstructural characterization through electron backscattered diffraction and transmission electron microscopy. The results revealed a reduction of twin boundaries with increasing plastic strain, indicates a non-twinning deformation mechanism which is different from the deformation twinning observed in other high speed forming process. The physical origin of the present phenomenon is discussed in detail according to the energy barrier and the critical shear stress that are required for the nucleation of perfect and partial dislocations that determine the formation of twins.

1. Introduction

The deformation conditions are critical to determine the deformation behavior, microstructure, and deformation mechanism of materials [1–4]. For example, twining and dislocation slip are two competitive mechanisms in crystalline materials, by comparison with dislocation slip, the deformation twinning in *f.c.c.* metals with medium–high stacking fault energy (such as copper) usually happens under extreme experimental conditions of low temperature, high strain rate and sufficiently high pressure etc., wherein the recovery of atoms is suppressed, facilitating the occurrence of deformation twins [5]. Meyers et al. [6] found that the coarse copper grains can reduce the critical stress for twinning, facilitating the occurrence of mechanical twins during dynamic deformation. Li et al. [7] revealed that large strain, low temperature, together with high strain rate, can induce high driving stress that enhances the nucleation of twins. Hong et al. [8] reported that deformation twins tend to occur in grains with large values of the Schmid factor for twinning system. It is worth noting that the mechanical twinning in *f.c.c.* copper also tends to occur under high strain rate (10^3–10^5 s^{-1}) deformations: explosive forming [6], laser shock loading [9], Split-Hopkinson bar (SHPB) [10] and other high velocity drop impact methods [7,8].

By comparison with these conventional high speed forming technologies, electromagnetic forming (EMF) is a new type of processing technique with strain rate ranging from 10^3 to 10^4 s^{-1} [11,12]. EMF has attracted enduring attentions and exhibited potential applications in modern manufacturing industries [12] due to its unique properties, such as contact-free force, low springback, high repeatability and enhanced forming limit [11–13]. Naturally, the questions then arise as to whether there is a mechanical twinning mechanism in copper under high speed electromagnetic forming, and what are the possible reasons?

In our previous work [14], pure cooper sheet was electromagnetically budged and the microstructural evolution after forming has been intensively investigated. It was found that the deformation under electromagnetic bulging is governed by dislocation slip, rather than the deformation twinning as expected in traditional high velocity forming as mentioned above [6–10]. However, the reason for the different deformation mechanisms under EMF and conventional high strain rate forming is still unanswered. In the present work, the physical origin of this non-twinning deformation mechanism of pure copper under high speed electromagnetic forming is investigated, and understood deeply in terms of the energy barrier and the critical shear stress of the nucleation of a partial and a perfect dislocation loop.

* Corresponding author.
E-mail address: hslining@mail.hust.edu.cn (N. Li).

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2. Experimental procedures

A commercial pure copper (purity 99.9%) sheet with thickness of 1 mm was selected in this work. The copper sheet specimen was firstly cut into a disk shape with diameter of Φ180 mm, and then annealed at 973 K for 120 min in argon atmosphere to eliminate the possible high density dislocations and fiber-like structures caused by pre-rolling process. The experiments were performed on a self-made EMF system with a maximum discharge voltage of 25 kV, capacitance of 80 μF and inductance of 200 μH, the schematic diagram of the electromagnetic forming apparatus is described in Fig. 1. The copper sheet was electromagnetically budged at ambient temperature under charge voltage of 17 kV. The detailed process of the experiments was described elsewhere [14].

The grain boundary characterization and the corresponding deviation of misorientations of the deformed specimens were probed by electron backscatter diffraction (EBSD) that is conducted using a field emission scanning microscope (FSEM, FEI Sirion 200) equipped with an EBSD detector. The samples for EBSD investigation were electrolytically polished in an electrolyte of 25% phosphoric acid, 25% ethanol and 50% distilled water under 4 V at ambient temperature. The measurements were carried out with an EBSD step size of 1.0 μm. The microstructural evolutions of the deformed copper were further characterized by transmission electron microscope (TEM, FEI 200 kV Tecnai G20). TEM thin foils were first ground mechanically to about 50 μm thick, followed by a twin-jet polishing method in the same electrolyte used in EBSD at 4–6 V and at ambient temperature.

3. Results and discussion

The general metallographic morphology of the annealed copper sheet was characterized, as depicted in Fig. 2, from which some annealing twin boundaries signed by blue arrow can be clearly observed. Fig. 3 describes a conical shape workpiece after electromagnetic bulging, accompanied with the corresponding distribution of plastic strain. It can be seen clearly that the effective strain shows an increasing trend from the bottom to the top of the bulged sample. Two typical zones A and B with effective plastic strain (ε) of 23% and 51%, respectively, were selected for micro-structural examinations.

It was reported [15] that the twin boundary has a $\sum 3$ misorientation and {1 1 1} grain boundary plane. In the present work, the high angle (>15°) and $\sum 3$ boundaries are concerned, as marked by blue and black lines respectively in Fig. 4. Fig. 4a–c describes the variation of grain boundary character distributions with plastic strains. It can be seen clearly that there are lots of $\sum 3$ boundaries

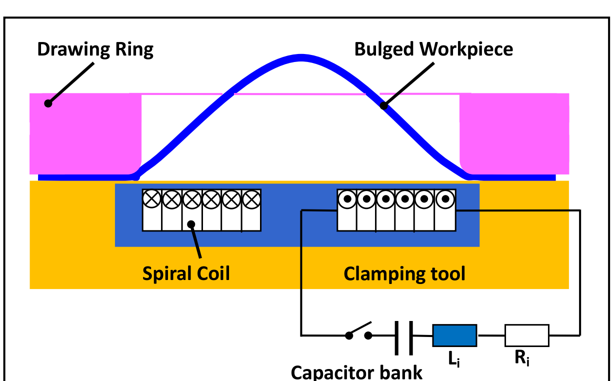

Fig. 1. Schematic diagram of the electromagnetic forming apparatus.

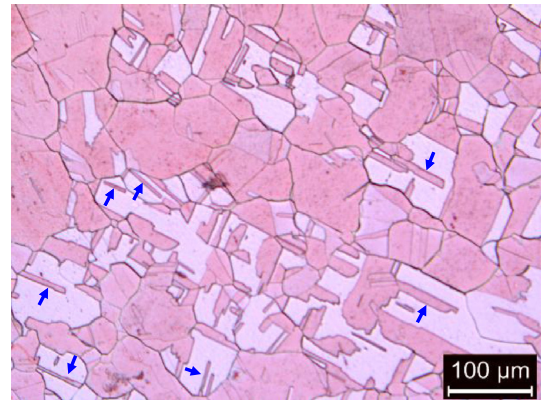

Fig. 2. Metallographic picture of the annealed copper sheet.

distributed in the annealed copper with a statistical fraction (*f*) of about 64.8%, as depicted in Fig. 4a. However, the fraction of $\sum 3$ boundaries decreases conspicuously after electromagnetic forming, and this tendency becomes more prominent with further increase of plastic strain. For instance, the percentage of $\sum 3$ boundaries decreases to 31.2% at strain of 23% (Fig. 4b) and 11.7% at strain of 51% (Fig. 4c). The reduction of $\sum 3$ boundaries indicates that part of the twin boundaries in pure copper disappeared during the EMF process, which can be understood simply in terms of the glide-twinning interaction theory [16] on the basis of original Thompson notation [17], as illustrated in Fig. 4g. Supposing that the dislocation $B\gamma$ on *ABD* plane is a twinning dislocation, the following reactions can be expressed as [17]:

$$CB \rightarrow C\delta + \delta B \quad (1)$$

$$\delta B \rightarrow \delta\gamma + \gamma B \quad (2)$$

The above dislocation reactions, starting with the initial incident dislocation *CB*, generate a mobile untwining dislocation γB. These reactions will untwin the twin lamella layer by layer until the twin disappears completely.

Furthermore, the deviation of misorientations for all $\sum 3$ boundaries in deformation zones with various plastic strains to the ideal relationship is shown in Fig. 4d–f. As discussed by Cullity [18], the ideal twin orientation for *f.c.c.* metals is a 60° rotation about a ⟨1 1 1⟩ twin axes. In terms of the deviation angle ($\Delta\theta$) to the ideal twin misorientation, $\sum 3$ boundaries could be divided into two groups: "twin" type ($\Delta\theta < 2°$) and "non-twin" type ($\Delta\theta > 2°$) [19]. Based on a 2° tolerance deviation from the ⟨1 1 1⟩ plane normal, all $\sum 3$ boundaries in the annealed sample belong to the "twin" type, as depicted in Fig. 4d. However, $\Delta\theta$ of most $\sum 3$ boundaries increases to above 2° in the deformed samples (see Fig. 4e and f), indicating a transition from "twin" type to "non-twin" type. It is proposed that this transition may originate from the lattice curvature induced by dislocations creation at twin boundaries during the plastic deformation [20].

In order to further clarify the reduction of twins during EMF, the microstructure of the deformed specimens with various plastic stains were examined by TEM, and the results are depicted in Fig. 5. It can be seen clearly that in the electromagnetically formed specimens with various strains of 23% (Fig. 5a) and 51% (Fig. 5b), no any visible twins can be detected but only dislocation cell structures.

According to the above experimental results, it is clear that the high speed electromagnetic forming of copper sheet does not follow a twinning deformation mechanism, but dislocation slip instead. This is quite different from the results observed in previous literatures [6–10], in which twinning is a common deformation mechanism in copper under high velocity processing. In general,