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Effect of crystalline anisotropy and forming conditions on thinning and rupturing in deep drawing of copper single crystal

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ABSTRACT

Copper single crystal has excellent electrical properties and ductility, and it has a peculiar application in micro-manufacturing. In this paper, a specific mold was designed and made in order to conduct deep drawing of copper single crystal and evaluate the crystalline orientation effect to the local thinning and rupturing in the process. As a contrast, a finite element subroutine (VUMAT in ABAQUS) based on the crystal plasticity theory was developed to simulate the deep drawing process according to the experimental configurations. The results show that the (1 1 0) blank has better deep drawing performance than (0 0 1) blank; The crack of (0 0 1) blank originates at ⟨1 0 0⟩ orientation in the plane because ⟨1 0 0⟩ orientation has poor plasticity; friction is a crucial factor to the forming quality in a small scale deep drawing process; the simulations are in good agreement with the experiments, which also indicates the crystal plasticity model is very necessary to study the plastic forming of metallic material, especially the crystalline characteristics should be considered in the research.

1. Introduction

A metallic single crystal owns atoms arraying regularly in space; so it has specific applications in lots of fundamental material and physics studies. Meanwhile, as they have several particular electrical and mechanical properties, metallic single crystals have been used in special mechanical manufacturing.

In many fabrication processes, plastic forming has some advantages such as high efficiency, bulk, low cost and net forming. Copper single crystal has high purity (99.99%), low resistance and good ductility, which is suitable to be deep drawn to form a cup-like part. In a deep drawing process, thinning and rupturing near bottom of the cup is a major defect, which would increase drawing force, reduce the quality of the product, and even make the product scrapped. The basic characteristics of thinning and rupturing in a deep drawing operation are similar as necking and fracturing in a tensile test. However, as the copper single crystal is not isotropic, the fracturing mechanism, the position of fracture and its extending orientation, would all rely on the crystalline anisotropy evidently.

Recently, the conventional scale deep drawing process and the damage evolution of materials by using various damage models were investigated. Gouveia et al. (1996) evaluated four previously published ductile fracture criteria in cold bulk metal forming. Tang et al. (1999) used a damage-based criterion derived by continuum damage mechanics (CDM) to predict the fracture limit of aluminum alloy Al 2024T3 sheet. Fan et al. (2006) implemented an elasto-plastic constitutive equation accounting for isotropic hardening coupled with material damage to simulate deep drawing of a mild steel square cup. As drawing operation conditions could affect the drawing quality severely, some works focused this aspect. For example, Tourki (1998) studied the friction effect to the orthotropic plastic sheet in deep drawing. Demirci et al. (2008) compared the results obtained from simulations and experiments, and they sought the best blank holding force.

Using various constitutive relations to describe the plastic anisotropy is an attractive topic in deep drawing simulations. Hill's yield function is frequently used to account for plastic anisotropy, because it has a simple formulation for numerical handling. However, owing to the cubic symmetry of the face centered cubic crystal system and crystal plane slipping feature, crystal plasticity constitutive model has more advantages than other constitutive model originating from classical yield surface theory, though it's numerical implementation would be very complicated. For example, Inala et al. (2000) simulated earing by polycrystal and a phenomenological model respectively. Zhao et al. (2001) suggested a texture component crystal plasticity finite element method for industry-scale anisotropy simulations, and then they (2004) revealed that the ear height and profile can be minimized by an optimized combination of certain texture components including their scatter. Grujicic and Batchu (2002) applied crystal plasticity simulation to model the as-rolled OFHC copper blanks and suggest to modify the blank shape to reduce the extent of the rim earing. Nakamachi

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et al. (2002) studied crystallographic texture on the formability and confirmed that crystalline plasticity FE code could predict strain localization and assess formability with good accuracy. Miehe and Schotte (2004) presented an novel constitutive stress update algorithms for single crystals and polycrystals at finite strains to investigate the deep drawing process of copper. Raabe et al. (2002) summarized the basic physical approaches of different method and discussed engineering aspects in the course of a forming simulation, and they (2004) presented a new finite element method which includes and updates texture during forming simulations. Tikhovskiy et al. (2007) used a texture component crystal plasticity finite element method (TCCP-FEM) to simulate the earing behavior in deep drawing process of sheet aluminum of the alloy AA 5754. Roters et al. (2010) reviewed crystal plasticity finite-element method for describing the elastic–plastic deformation of anisotropic heterogeneous crystalline matter. The main goal of above simulations is to show features of crystal plasticity finite element methods and investigate the influence of various texture components on the drawn part and texture evolution in deep drawing operations.

Copper single crystal has the same crystallographic orientation on each material particle prior to plastic deformation. The lattice orientation of each particle inside the material will rotate gradually and individually in deformation procedure. The aim of this study lies in an investigation of thinning and rupturing during deep drawing of copper single crystal blank by conducting a series of experiments and the crystal plasticity finite element simulations. The plan of the paper is as follows: Firstly, a specific mold is designed and made; some experiments of deep drawing process are presented. Secondly, finite element simulations of deep drawing based crystal plastic theory are conducted. Finally, the results obtained from experiments and simulations are analyzed to study the effect of drawing process parameters and crystalline orientation of the blank on the thinning and rupturing of the drawn cups.

2. Experimental setup and deep drawing conditions

2.1. Material and specimen preparation

Copper single crystal (99.99% purity) was supplied in the form of directional solidification rod with diameter of 30 mm. The orthogonal crystal orientations, [1 0 0] and [0 1 0] are located in the cross section; the [0 0 1] orientation is the same as axial direction of the rod. The original crystallographic orientation in the rod had been marked by the material supplier (shown in Fig. 1). Raabe et al. (2004) discussed the influence of the initial crystalline orientation scatter in a single crystal. For simplifying the problem, the initial orientation scatter in this single crystal was not measured and its influence was not included. The small blanks to be punched were cut from the rod by wire EDM, then grinded and polished. Finally, the blanks have the circular shape with diameter of 8 mm and thickness of 0.3 mm.

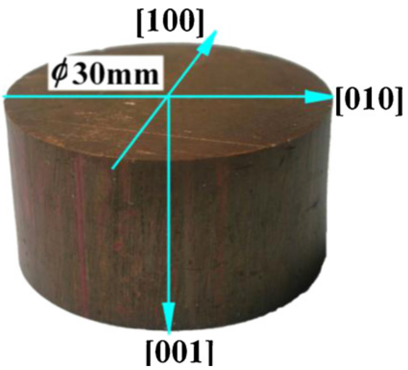

Fig. 1. The copper single crystal ingot and crystal orientations.

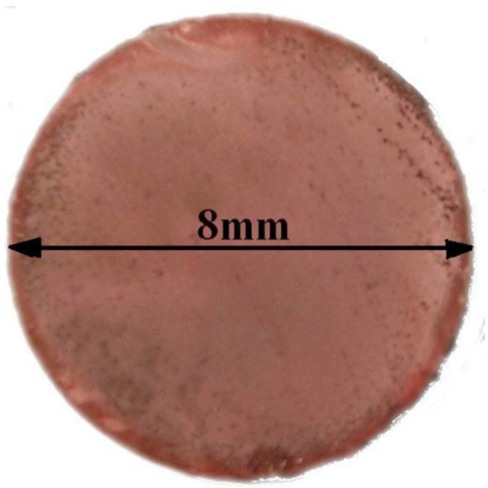

Fig. 2. Metallograph of copper single crystal after etching. No grain boundary exists.

The blanks were put into the etching liquid ($FeCl_3$ 5g + HCl 15 ml + H_2O 60 ml), no grain boundary could be observed in the section (shown in Fig. 2), which demonstrated the material is a single crystal.

In order to investigate the crystalline orientation influence on the material mechanical properties, some small tensile specimens were cut from the ingot section and the tensile axis were defined along as the [1 0 0] or [1 1 0] orientation respectively. Fig. 3 clearly shows the specimen of [1 1 0] is more ductile than that of [1 0 0].

Two groups of blanks with different crystalline orientation were cut from the ingot. For group A, the (0 0 1) plane is the punched plane, so the [0 0 1] orientation is defined as punch force direction; for group B, the (1 1 0) plane is the punched plane and [1 1 0] orientation as punch force direction. For later describing the different group conveniently, group A was named (0 0 1) blank and group B was named (1 1 0) blank (Fig. 4).

2.2. Deep drawing mold

A specific mold was designed and made to satisfy the experimental conditions. The mold can be fixed on a universal material

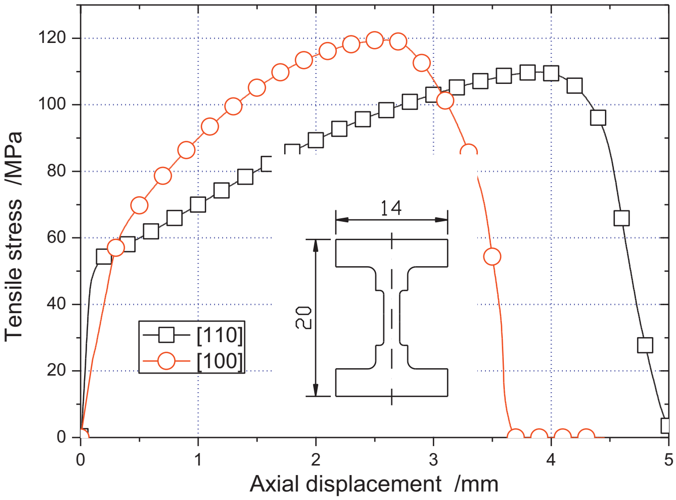

Fig. 3. Tensile curves of two typical crystalline orientations.