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# Effect of stress profile on microstructure evolution of cold-drawn commercially pure aluminum wire analyzed by finite element simulation

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ABSTRACT

The evolution of microstructure in the drawing process of commercially pure aluminum wire (CPAW) does not only depend on the nature of materials, but also on the stress profile. In this study, the effect of stress profile on the texture evolution of the CPAW was systematically investigated by combining the numerical simulation and the microstructure observation. The results show that the tensile stress at the wire center promotes the formation of <111> texture, whereas the shear stress nearby the rim makes little contribution to the texture formation. Therefore, the <111> texture at the wire center is stronger than that in the surface layer, which also results in a higher microhardness at the center of the CPAW under axial loading.



## 1. Introduction

Commercially pure aluminum wire (CPAW) is an important carrier for transmitting electric power over long distances, which is achieved by a standard multi-pass cold drawing process. Fracture is the main failure mode of CPAW due to the dead weight, wind load and ice load during the actual service process [1,2]. Therefore, the most effective way to improve the service safety of the CPAW is to enhance the mechanical properties. As the mechanical properties of metals commonly depend on the microstructure under different processes, for the pure aluminum, studies on the mechanical properties and the microstructure evolution attracted wide attention [3–5].

Under the different processing conditions, the microstructure evolution can markedly affect the mechanical properties of pure aluminum and its alloys [6,7]. As reported by Hou et al. [8], dislocation multiplication, <111> texture evolution and the increasing high-angle grain boundaries could significantly improve the strength of the pure aluminum wire during the multi-pass cold drawing. Meanwhile, many researchers used severe plastic deformation (SPD) techniques to process the commercially pure aluminum, such as equal-channel angular pressing (ECAP), high-pressure torsion (HPT) and accumulative roll-bonding (ARB). Their results showed that after the above processing, the dislocation density increased significantly, the grain size decreased continuously, the crystallographic orientations were also changed, then the mechanical properties were improved significantly for the commercially pure aluminum [9–12]. Furthermore, the mechanical properties of aluminum alloys and copper after SPD processing were also enhanced due to the texture formation, the grain refinement and the high density of dislocations [13–15]. Hence, the controlling the microstructure evolution of the pure aluminum wire can effectively affect the mechanical properties during the cold drawing process.

The plastic deformation of each drawing pass is an important parameter that affects the microstructure evolution of the pure aluminum wire. For the wire drawing process, the plastic deformation usually depends on the stress state of the wire in the drawing die. Therefore, the stress profile in the wire when it gets through the drawing die is the key factor that determines the microstructure evolution of the CPAW during the multi-pass cold drawing. In the field of metal deformation, such as rolling and drawing,

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**Table 1**
Diameter and area reduction of CPAW in each pass.

| Pass | Diameter (mm) | Area reduction (%) |
|---|---|---|
| 0 | 9.89 | 0 |
| 1 | 8.12 | 32.6 |
| 2 | 6.98 | 50.2 |
| 3 | 6.60 | 55.5 |
| 4 | 5.79 | 65.7 |
| 5 | 5.27 | 71.6 |
| 6 | 4.56 | 78.7 |
| 7 | 3.97 | 83.9 |
| 8 | 3.60 | 86.7 |
| 9 | 3.25 | 89.2 |

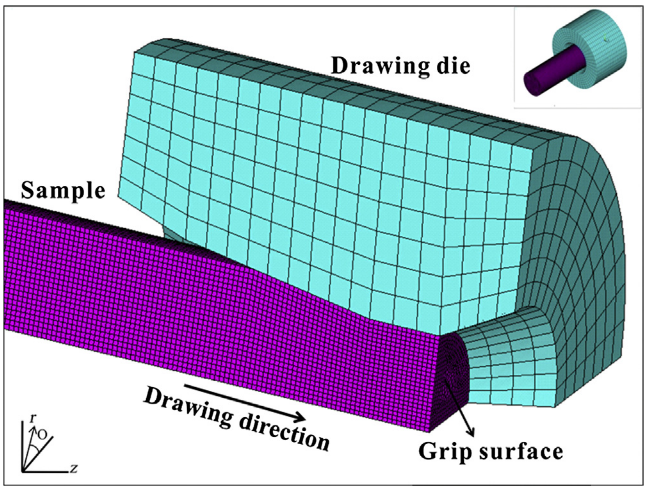


**Fig. 1.** Finite element model of wire in drawing die.

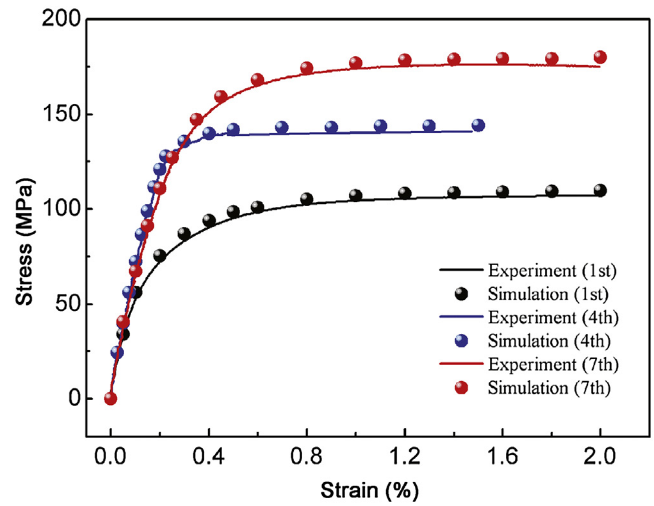


**Fig. 2.** Comparison of experimental stress-strain curves with simulated results.

finite element method (FEM) has been proven to be an efficient and reliable analysis method [16–18]. The FEM can accurately simulate the nonlinear problem in the drawing process, particularly the plastic deformation and the corresponding stress profile in the workpiece [19,20]. Some researchers paid much attention to the residual stress profile in the cold-drawn wires, and the impact of the residual stress on the mechanical properties [29,30]. However, the influence of stress profile on the microstructure evolution and mechanical properties of wires during the drawing process is rarely discussed before.

In this study, using the parameters obtained from the mechanical tests, a finite element analysis model was established, and subsequently the stress profile and plastic deformation behavior of the CPAW were analyzed using the LS-dyna software. The mechanism for the microstructure evolution and the variation of the microhardness were discussed combining the microstructure observations and finite element analysis. This study may help to better understand the relationship between the stress profile and microstructure evolution during the multi-pass cold drawing of the CPAW.

## 2. Experimental and numerical procedures

### 2.1. Experimental procedure

An A6 commercially pure aluminum rod with the original diameter of 9.89 mm was chosen as the object of research in this study, and the final aluminum wire with a diameter of 3.25 mm was manufactured by the cold drawing process for 9 passes on a bull block drawing machine. The total area reduction is about 89.2%. The drawing die parameters and the area reduction of the wire in each pass are listed in Table 1.

In each pass, samples with their gauge lengths of 150 mm were fabricated for the uniaxial tensile tests, which were carried out on a Shimadzu AG-X testing machine with a constant strain rate of $1.0 \times 10^{-3}\ s^{-1}$ at room temperature. The tensile axis was parallel to the drawing direction and in each team three samples were prepared.

Four types of wires with the area reduction of 32.6%, 65.7%, 83.9% and 89.2% were chosen for the characterization of microstructure, especially the evolution of the texture formed during the cold drawing. For characterizing the microstructural evolution of the CPAW, thin sheets with the thickness of 3 mm were cut from the CPAW in the drawing die along the longitudinal direction. Then, samples were polished with 2000-grit SiC paper and then electrolytic polished using an etching solution containing 10% perchloric acid and 90% alcohol in volume. The microstructure and texture evolution were analyzed by the EBSD technique integrated in a ZESIS SUPRA 35 scanning electron microscope (SEM). Finally, the microhardness values of the wire along radial direction through the center of the wire from the core to the surface were measured by an AMH43 automatic micro hardness.

### 2.2. Numerical procedure

#### 2.2.1. Numerical model: the drawing process simulation

The mechanics in the drawing process of the CPAW is a multiple nonlinear coupling problem including the geometric nonlinear and the contact nonlinear. A numerical model using the code LS-dyna was developed to analyze the stress profile within the aluminum wire during the drawing process. To diminish computational time, the finite element model was defined as 1/4 axisymmetric model, and made use of LS-dyna 8-noded explicit integration elements with multi-point Gauss integral, and then special care was taken in choosing this element for avoiding the well-known volumetric locking problem [21]. The drawing dies were treated as the rigid bodies and the CPAWs were defined as the deformable bodies. The contact between the die and the CPAW was defined as a Coulomb contact. The range of contact friction coefficient is generally from 0.01 to 0.2 in industrial practice, and studies have shown that there is no significant influence on the results when the friction coefficient was changed in this range [21,22]. Uniform displacement at the grip surface of the CPAW was defined as boundary condition in order to simulate the drawing process under displacement control when the grip surface was pulled through the drawing die. Besides, the starting and the ending part of the CPAW were ignored, and we only focused on the case that the middle position of the wire