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Microstructure of the pure copper produced by upsetting with ultrasonic vibration

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ABSTRACT

The propagation of the ultrasonic wave in the solids can greatly affect the microstructure of the material. In this paper, upsetting with ultrasonic vibration as a novel method to produce the ultrafine grained material was presented to refine the pure copper grains. For the ultrasonic vibration upsetting, during the upsetting process, the ultrasonic wave propagates in the specimen at the same time. Under the coupling action of the ultrasonic and plastic deformation, the pure copper grains with the initial grain size of ~50 μm? were refined to about 100–300 nm after one time forming process. By comparing the ultrasonic vibration upsetting with the conventional upsetting process, the role that the ultrasonic wave played during the upsetting process was revealed.

1. Introduction

Ultrasonic energy is mechanical energy. When the wave transmits in the solid, it can create an additional stress field in the material [1]. From the time of 1960's, many scientists begin to investigate the effect of the ultrasonic on the material micro-structural and mechanical properties. Noticeable contributions to the investigation of these processes were made by N.A. Tyapunina [2,3], I.G. Polotskii [4–6], and others. It was shown that ultrasonically induced stress in NaCl and LiF crystals with the amplitude exceeding their yield strength enhances dislocation density. For the polycrystalline metals with fcc lattice (Al, Cu, and Ni), they also found that dislocation density linearly increased beginning from a particular peak stress threshold σ_{mt} close, at least for Cu and Ni, to their yield stress. When the density of the dislocations is high enough, an alignment of dislocations occurs. It has been observed that a distinct cellular structure, about 2 μm in size, is formed in ultrasonically treated aluminum monocrystals after it was exposed to ultrasonic vibration for only 8 s [7]. Kulemin [8] investigated the effect of a 20 kHz ultrasonic on the mechanical properties of metals with the fcc lattice. The studies shown that ultrasonic vibrations with the stress amplitude exceeding a threshold value specific for a given material act to harden an annealed metal, the yield and breaking strengths being increased.

In these years, interests are still focused on improving the material mechanical properties. From the Hall–Petch equation we know, the material properties can be greatly improved by refining the materials grains. Due to nanostructured materials offer unique and entirely different mechanical, electronical, optical, and magnetic properties compared with conventional micro- or millimeter-sized materials, many works have been done to refine the materials grains. Traditional methods for producing nanostructured materials include gas atomization and ball milling followed by consolidation, and rapid solidification [9,10]. However, these processes tend to be expensive and capable of fabricating only small amounts of material. Recently, severe plastic deformation has been increasingly applied for producing the ultrafine grained (UFG) materials [11,12]. Equal Channel Angular Pressing (ECAP) is one of the methods that use severe plastic deformation to produce nanostructured materials, but the size of the sample is limited due to the high friction forces that exist between the material and the wall [13]. Moreover the efficiency is very low for this process, the samples should be pressed through the channel at least 4 or more times to make the grains size to reach to the nano-scaled level.

So, based on the research mentioned above about the ultrasonic and sever plastic deformation, our research idea is that combine the affect of ultrasonic vibration and plastic deformation to get nano-scaled materials grains. In other words, we apply ultrasonic wave to propagate in a part, and at the same time, make the part to have a plastic deformation. In this paper, the experiment of the UUV was conducted and the microstructure of the sample was observed. By comparing the forming processes of the UUV and the conventional upsetting (CU), the role that the ultrasonic vibration played in the upsetting process was revealed.

2. Experimental

Fig. 1 shows the schematic of the ultrasonic vibration upsetting and the part formed by this forming process. In this experiment, the ultrasonic generator, which can provide the ultrasonic vibration with the

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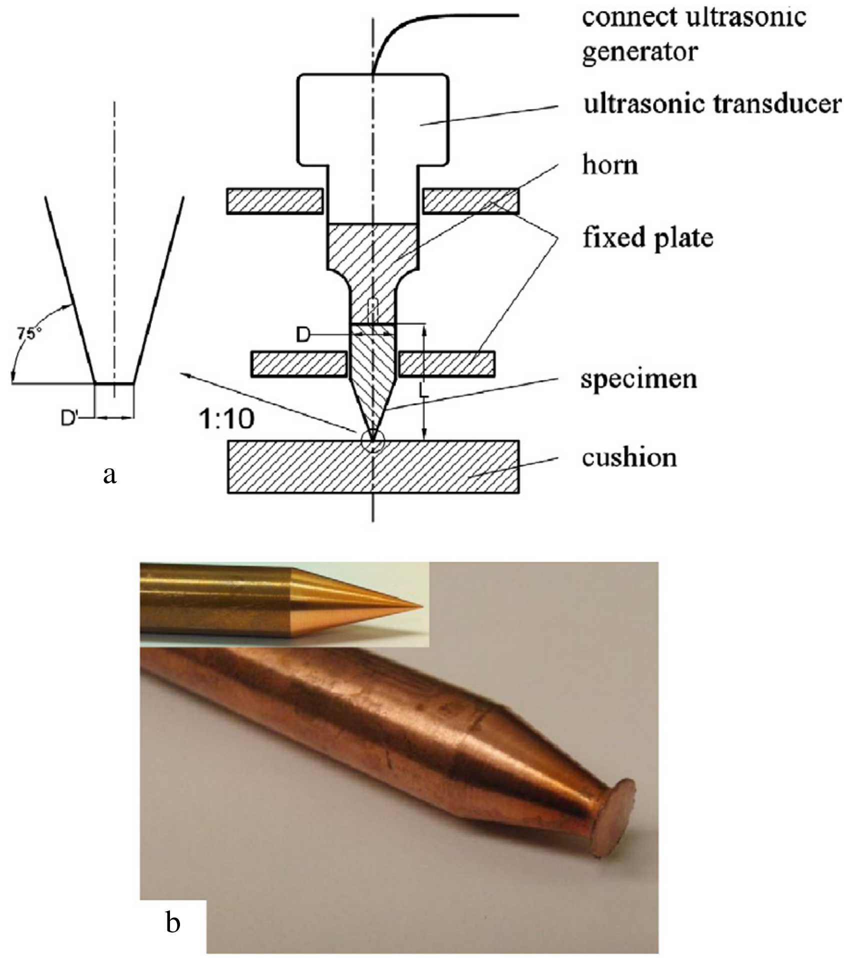

Fig. 1. a): Schematic of the upsetting with ultrasonic vibration and b): the parts formed by this forming process.

frequency (f) of 20 kHz, horn, specimens were combined together as a whole part. Two fixed plates were used to make these parts stand vertically on the cushion. The specimen contacts with the horn tightly, so the initial ultrasonic energy can be directly injected into the specimen.

High purity copper (99.99 wt.%) was selected for the present study. Due to the supplied copper was in a cold-drawn state, an annealing treatment was performed (700 °C for 2 h), giving a grain size of ~50 μm (as shown in Fig. 2). Several twins were present within the grains. Bars of the as-received material were then machined to obtain the cone tips. The dimensions of the specimens are shown in Fig. 1a, the length of the rod L was 145 mm, the rod diameter D was 12.7 mm, and the cone tip diameter D' was about 0.5–1 mm. The rod with these dimensions just had a self-frequency of about 20 kHz, so it can be resonated when the ultrasonic generator is working. Moreover, the tip of the specimen, carrying the total weight of the specimen and ultrasonic unit, was in point contact with the steel substrate. Due to the self-weight of the parts, a large external compressive stress was built on the tip, ensuring that the stress at the tip was largely compressive during ultrasonic vibrations.

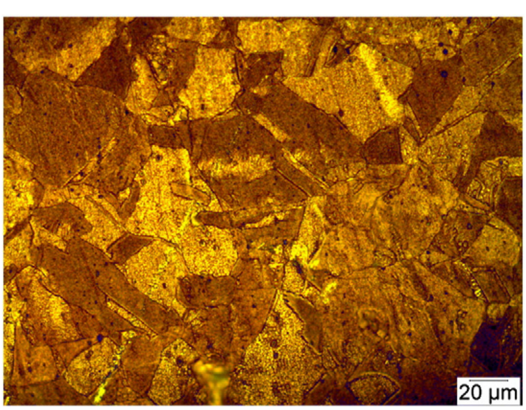

Fig. 2. Optical micrographs of the as-annealed 99.99% copper.

UUV experiment was conducted at room temperature, high intensity ultrasonic energy was injected into the specimen for 60 s, and then severe plastic deformation was occurred in the tip. During the forming process, coolant was used to avoid the elevated temperature.

After the UUV process, the coin tip had been largely deformed and just looked like an umbrella as shown in Fig. 1b. Microstructures of the deformed region of the tip were observed using optical microscopy and transmission electron microscopy (TEM). The TEM samples were prepared from the top surface of the deformed region of the rod by the FIB (Focused Ion Beam) lift-out method in an FEI NovaLab 200 FIB system. The initial thinning was performed at voltage of 30 kV current of 0.3 nA. The final thinning was performed at lower voltage and current (10 kV, 23 pA) to decrease the damage from Ga ion beam on the sides of the sample. To characterize the mircostructure, transmission electron microscopy was carried out using an FEI Tecnai operated at 200 kV.

3. Results and discussion

TEM observations confirmed the presence of grains with highly deformed morphology after the plastic deformation as shown in Fig. 3. Some grains with the size of about 100 nm and many subgrains were existed as shown in Fig. 3a. In Fig. 3b, lots of tangled dislocations