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Efficient fabrication of gradient nanostructure layer on surface of commercial pure copper by coupling electric pulse and ultrasonics treatment

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ABSTRACT

Severe plastic deformation can be easily produced on metal surfaces by coupling the micro thermal shock from high peak pulse current and the micro mechanical shock from ultrasonics. Moreover, an efficient method for preparing a gradient nanostructured metal surface by coupling electric pulse and ultrasonics treatment (CEPUT) is developed in this study. The variation in microstructure and hardness of the specimen are investigated by electron backscatter diffraction, transmission electron microscope, X-ray diffraction, and nano-indentation measurement. Results showed that on the treated copper surface with CEPUT, the original grain boundaries are no longer recognized, the average grain size decreases from 48.77 μm to 39.22 nm, and the thickness of severe plastic deformation layer reaches to approximately 500 μm. Moreover, the hardness reaches to 2.105 GPa, and CEPUT also reduces the texture in the sample surface. A computational model is developed and the grain refinement mechanism is proposed to describe the electrical-thermal-mechanical phenomena during CEPUT. The proposed simple and cost-effective method of grain refinement and to produce the graded materials is effective, especially in the materials of high thermal and electrical conductivity.

1. Introduction

Metallic materials with nanometer grain size (average < 100 nm) in the top surface have attracted intensive research due to their superior physical and mechanical properties and improved service life [1–6]. The metallic materials' nanostructure surface is important for increasing their service life because many failures originate at or near the materials' surface.

In recent years, mechanical treatment methods, such as high energy shot peening [7], supersonic fine particles bombarding [8], surface mechanical attrition treatment (SMAT) [9], high-pressure torsion [10], platen friction sliding deformation [11], have gradually attracted significant interest from researchers. On the basis of the above-mentioned methods, severe plastic deformation (SPD) and a lot of crystal defects have easily occurred in the metal surface in which the surface grain size is reduced to nanoscale and the gradient nanostructure (GN) layer is generated at the metal surface. Moreover, the adhesion force between the nanocrystalline surface layer and metal matrix is good. Furthermore, low plasticity burnishing [12] and water jet cavitation peening [13] are common technologies that cause SPD at the surface region to generate a GN surface layer on metallic materials. Thus, these technologies have attracted considerable attention recently.

Ultrasonic vibration energy could significantly soften the metallic materials without significant heating, which is usually termed as acoustoplastic or acoustic softening effect. From its first observation, ultrasonic vibration energy has been widely used to assist the plastic deformation and improve the material flow in metal processing using SPD methods [14–16]. Liu et al. [17] applied ultrasonic waves on a plastic deformation area during its conventional upsetting to refine material grains. Their experiment and simulation results showed that the produced stress by ultrasonic

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vibrations increased the plastic deformation. Djavanroodi et al. [18] investigated the effect of ultrasonic vibrations on the deformation behavior of pure commercial aluminum in the equal channel angular pressing process. They determined that the forming force decreased with the increase of vibration amplitude and vibration frequency. Moreover, ultrasonic assisted equal channel angular extrusion [19], ultrasonic impact treatment [20,21], ultrasonic surface rolling process [22], and ultrasonic nanocrystal surface modification [23] were investigated, and the results indicated that ultrasonic vibrations induced SPD and improved the grain refinement efficiency in SPD processes.

Laser shock processing (LSP) is a surface treatment technology, and the mechanical effect of a laser shock wave with high-instantaneous-energy-density induces high compressive residual stress and microstructural evolution that generate nanocrystal grains on the metal surface [24,25]. However, a confined medium and a coating layer required on the metal surface during LSP complicate the process.

The electroplastic effect induced by a high-density pulse current in metals was discovered in the 1960s, and its mechanism has been investigated for decades [26–28]. Moreover, the electroplastic effect can decrease the flow stress, improve the deformation limit of metallic materials, and enhance the mobility of dislocations, atomic diffusion and vacancy diffusion. Thus, the electroplastic effect has been recognized due to its high efficiency and has attracted extensive studies in materials science and engineering, such as rolling, drawing, and refining grain [29–33].

On the basis of the above mentioned grain refinement methods, SPD were caused by either the applied loads, the instantaneous heat, or the electroplastic effect, and grain refinement methods experienced low processing efficiencies that hindered the widespread application of surface nanocrystallization methods. In this study, we find that SPD is easily produced and significantly enhanced on metal surfaces by coupling the micro thermal shock from high peak pulse current and the micro mechanical shock from ultrasonics. Moreover, an efficient method for preparing a GN metal surface by coupling electric pulse and ultrasonics treatment (CEPUT) is developed, and the preparation mechanism and the physical characteristics of a GN layer are investigated.

The rest of the paper is structured as follows: Section 2 describes the principle, experimental details, and numerical simulation of CEPUT, and the structural characterization and nano-indentation test of the sample after CEPUT. Section 3 illustrates the microstructure of the copper sample after CEPUT and the grain refinement process, and analyzes the performance of the treated copper sample to provide insight on the mechanism and advantage of the CEPUT method. Section 4 provides the conclusion.

2. Material and methods

2.1. Principle of CEPUT

The physical model and experimental device for CEPUT are shown in Fig. 1. As depicted in Fig. 1A, the heat from electric pulse and the force from ultrasonic vibration both act on the sample surface by tool impacting. The electric current transiently increases during the electric pulse (Fig. 1B), and the contact resistance is high at the contact point. Thus, the temperature rapidly increases at the contact point. The electric current duration is very short, the electric current rapidly decreases, and the working fluid is flushed to the contact point between the tool and the sample with a nozzle at room temperature. Thus, the temperature at the contact point rapidly decreases, and the high temperature gradient and the high thermal stress are obtained during CEPUT. High equivalent stresses are generated at the contact point coupled with continuous ultrasonic shocks. Meanwhile, the high peak pulse current (Fig. 1B) at the contact point makes the electron within the material rapidly move along the electric field, and the produced large electron-wind-force assists the dislocation motion and opens the tangles of dislocations due to the electroplastic effect [34,35]. Thus, the deformation resistance significantly decreases, the plasticity is significantly enhanced, and SPD easily occurs that contribute in grain refinement to produce a nanocrystalline layer on the metal surface. In this study, the mechanical force is composed of the preload pressure from air and the ultrasonic vibration impact force from the tool, the heat is generated by the high-instantaneous-energy-density pulse current during CEPUT, and the developed experimental device for CEPUT is depicted in Fig. 1C. As shown in Fig. 1C, the experimental sample rotates at velocity V_1, and the treatment tool is forced on the sample surface and slides along the sample axial direction at velocity V_2. The treatment tool and the sample are connected to the positive and negative poles of the

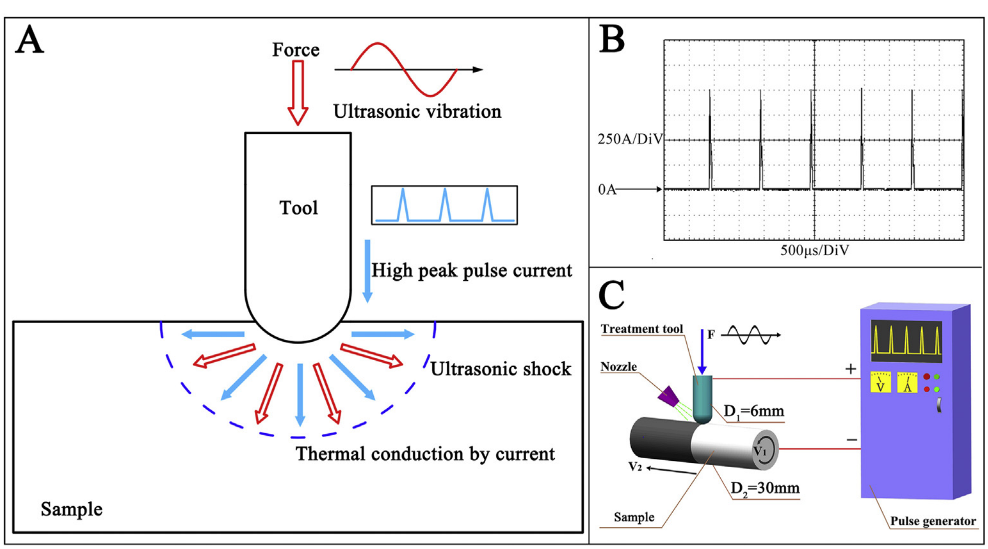

Fig. 1. Physical model and experimental device for CEPUT. (A) Physical model, (B) Pulse current waveform, (C) Experimental device.