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Ultrasonic assisted equal channel angular extrusion (UAE) as a novel hybrid method for continuous production of ultra-fine grained metals

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ABSTRACT

The propagation of high-intensity ultrasonic vibration (UV) into metals can influence on mechanical and microstructure properties. The main objective of this research is to introduce a new hybrid method for improving limitations of the conventional equal channel angular extrusion (CECAE) process by using superimposed ultrasonic vibration on billet in the plastic deformation zone (PDZ) directly. The experimental set-up was designed and fabricated for the UAE process of commercially pure aluminum (99.5%) with two distinct wave propagation directions as laterally (L-UAE) or vertically (V-UAE). By combining of high-intensity UV with the ECAE process, ultra-fine grained (UFG) aluminum with grain size about $\sim 2\ \mu m$ was attained only with one pass, enabling even higher values of microhardness on processed samples. Moreover, the required load with UAE was about 30% lower than CECAE. Finite element simulations further confirmed the more plastic deformation during UAE than CECAE. The use of UV vertically against extrusion direction (V-UAE) showed better homogeneity in strain, grain size and hardness distributions.

1. Introduction

Severe plastic deformation (SPD) process is an efficient technique for grain refinement of metals by imposing high shear strain. Equal channel angular extrusion (ECAE) as one of the most common SPD methods, was first introduced by Segal et al. [1] but the efficiency of ECAE is limited. Some of the limitations including high forming force, several passes to reach a fine grained structure, high friction forces, microstructural inhomogeneity and poor surface quality [2]. Therefore, it is of interest to enhance the efficiency of this process. The application of ultrasonic vibration as a high-frequency mechanical wave to improve manufacturing processes has received considerable research interest in recent years [3]. Several reports have been published about experimental and modeling of ultrasonic-assisted metal forming processes such as compression and upsetting [4,5], wire drawing [6], deep drawing [7], hot extrusion and micro-extrusion [8,9]. Although, the main goal of most previous researches has been the reduction of forming force by using ultrasonic surface effects [6,7,10,11], few efforts have been established to investigate the effect of high-intensity ultrasonic vibration on microstructural change during plastic deformation of metals. For example, Siu et al. [12] reported softening effect and subgrain formation with size about 1–2 μm in ultrasonic assisted micro-indentation. Also, Liu et al. [4] obtained severely deformed nanostructured (NS) copper by combining upsetting with ultrasonic vibration (UUV).

The main objective of this paper is to introduce a new hybrid method entitled ultrasonic-assisted ECAE (UAE) to improve efficiency of CECAE method by effectively applying ultrasonic vibration in the PDZ in two distinct directions.

2. Principle of UAE

Unlike the CECAE process, UAE die is designed to have three channels: billet input channel, product output channel and a new channel for ultrasound horn inlet. The billet is pressed by punch through the die channel while it experiences high-intensity UV in the main PDZ. For the designed die, billet in the PDZ can be excited by ultrasonic wave in two separate directions as lateral or vertical excitations which are entitled L-UAE and V-UAE respectively as shown schematically in Fig. 1(a and b). In the UAE process, the material elements undergo a severe plastic shear strain with superimposed high-impact pressure through the passing shear plane. The peak value of the imposed pressure can be predicted by $P^{*}=\lambda.\ \omega.\ \rho.\ c$ [13], where λ, ω, ρ and c are vibration amplitude, angular frequency, density of metal, and wave velocity on metal,

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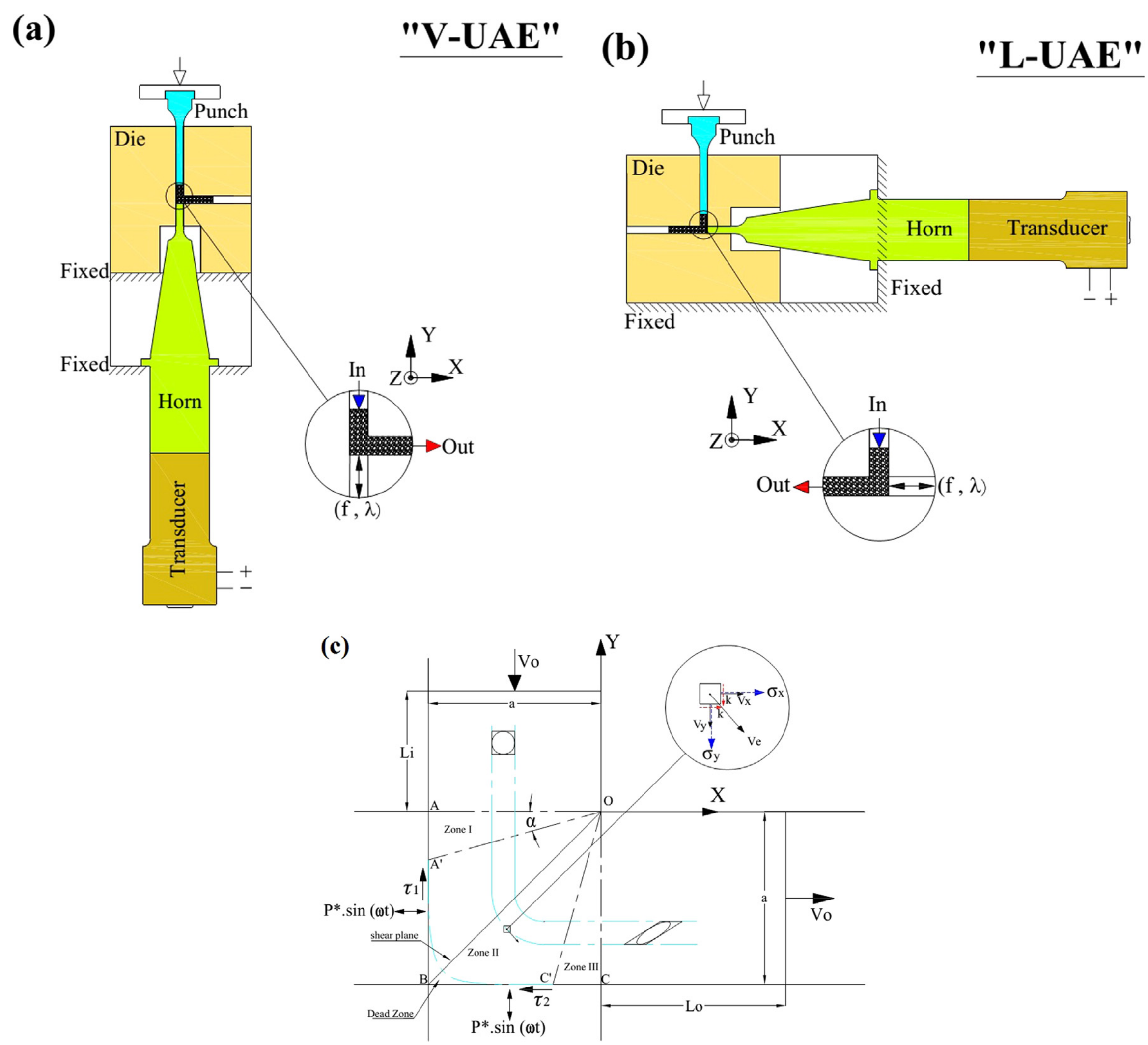

Fig. 1. The schematic view of ultrasonic-assisted ECAE with: (a) vertical vibration (V-UAE), (b) lateral vibration (L-UAE); (c) Deformation state during UAE processes.

respectively. From the macroscopic viewpoint, the actual velocity (V_{tot}) of a particle into the PDZ (OABC in Fig. 1c) is obtained by $V_{tot}=V_e+V_\nu$, where V_e is the static speed during UAE and V_ν is the additional vibrational speed based on UV. V_ν can be expressed as $\frac{\partial u}{\partial x}=\lambda.\ 2\pi f.\cos(\omega t)$, where u is vibrational displacement, λ is vibration amplitude and f is vibration frequency. From the microscopic viewpoint, plastic shear strain rate ($\dot{\gamma}$) variation can be described by modified crystal plasticity theory in a special slip system (α) with considering acoustic softening by [14]:

$$\dot{\gamma}^{(\alpha)} = \gamma_0{}^{(\alpha)}.\ sgn(\tau^{(\alpha)})\left\{\left|\frac{\tau^{(\alpha)}}{g^{(\alpha)}.\ U_{soft}}\right|\right\}^m \quad (1)$$

.where $\tau^{(\alpha)}$ is the resolved shear stress, $\gamma_0{}^{(\alpha)}$ and m are the reference strain rate and sensitivity exponent related to material properties, and $g^{(\alpha)}$ is the strength of slip system (α). U_{soft} is the ultrasonic softening coefficient with value smaller than 1 which causes the material to soften down during deformation due to ultrasonic energy. Therefore, higher values of strain rate and equivalent plastic strain of the material in the PDZ are expected during UAE. In addition, the surface effects of applying high-intensity UV can be predicted by observing the decrease of friction forces as normal and in-plan parallel vibrations in the PDZ (AB and BC surfaces in Fig. 1c) depending on the amount of velocity ratio ($\frac{V_e}{V_{cr}}$) and vibration amplitude (intensity), as detailed in Refs. [15,16].

3. Experimental procedure and FE model

Test samples of pure aluminum 99.5% were machined from sheet as 5×5 mm^2 section bars and 30 mm in length. Test samples were prepared by full annealing at 623 K for 2 h with initial average grain size ~160 μm as shown in Fig. 2a. The samples were polished and lubricated with MoS_2 grease. The high-frequency voltage required for UV is generated by a 3 kW ultrasonic generator. The transducer was designed and tested to vibrate at resonance condition with frequency about 20 kHz. The die angle (φ) and corner angle (ψ) were 90° and 3° respectively. The billet was pressed with extrusion speed of 5 mm/min. The CECAE tests performed without vibration, while L-UAE and V-UAE tests were conducted with vibration amplitude 15 μm. The microhardness tests were performed using Vickers indenter with a load of 100 g for a period of 10 s. The sectioned processed samples were cold-mounted and electro-polished (Electromet 4, Buehler Corp.) and then etched in Keller's solution to prepare for microstructural studies as well as microhardness measurements.

For finite element (FE) simulation, a commercial FE code Abaqus/Explicit as 2d a plain strain was used with a similar modeling process as the experiments. The stress-strain properties of pure