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Ultrasonic assisted tubular channel angular pressing process

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ABSTRACT

Improvement of severe plastic deformation method's efficiency by decreasing the pressing load is an important challenge for industrialization of these processes. A novel severe plastic deformation technique entitled tubular channel angular pressing process was recently proposed and experimented. The current study investigates the influences of ultrasonic vibration (UV) amplitudes in axial and radial directions on the deformation behavior and required punch force of TCAP process using finite element analysis. The numerical results indicated that the magnitude of imposed effective strain and the uniformity of strain distribution are enhanced by applying ultrasonic vibration. In addition, higher UV amplitude leads to an increment of effective strain and enhancement of strain dispersal. Furthermore, the simulated results showed that application of ultrasonic vibration needs lower pressing force to carry out TCAP process. Furthermore, a much lower punch load is required by adding vibration amplitude. It is found that the influence of radial directional UV is a more dominant factor than axial one on both the strain behavior and the pressing force. It is believed that ultrasonic vibration of TCAP die is more impressive than UV of either mandrel or punch.

1. Introduction

During the last two decades, the interest in enhancing material properties and characterizations has increased by grain refinement of materials using severe plastic deformation (SPD) techniques for various structural and fundamental applications [1,2]. As known, required pressing force (RF) is a prominent factor in all SPD methods, and other significant parameters also may affect this factor during the process. Hence, improvement of the SPD process efficiency by reduction of the processing load is an important challenge for industrial applications of ultra-fined grained (UFG) and nanostructured (NS) metals and alloys. One of the important tools to reduce the required punch force is applying ultrasonic vibration (UV) in the metal forming process. In general, it can be said that the reduction of required punch force is related to the stress superposition effect, rise in temperature and variations in the friction condition between the sample and die interfaces [3].

Up to now, the limited reports were published on the experimental and numerical analyses of ultrasonic vibration technique on the upsetting [4–6], extrusion [7,8], wire drawing [9,10], forging [11] and equal channel angular pressing [12,13] processes. Finite element modeling (FEM) and experimental works by Hung et al. [4] on the ring compression test using ultrasonic vibration showed that this technique can effectively reduce the material flow stress and increase the interfacial friction. Investigations of Liu et al. [5,6] indicated that the ultrasonic wave during the upsetting process leads to fabrication of UFG structure on the pure copper cone tips. Studies by Mousavi et al. [7] on the influence of ultrasonic vibration during the extrusion process demonstrated that the extrusion force and the material flow stress are lessened by applying UV if the extrusion speed is below the critical rate. Also, it can be found that applying ultrasonic vibration has no considerable effect on the equivalent plastic strain of the material. Explorations of Bunget et al. [8] pointed out that there is a good potential for using ultrasonic vibration as a tool to extrude difficult-to-lubricate materials during the micro-extrusion process. Hayashi et al. reported [9] that the UV wire drawing process causes better drawing resistance, improvement of lubrication state and reduction of wire breakage and, also, leads to handling the drawing of difficult-to-draw materials. The influence of radially and axially ultrasonic vibration on the wire drawing process (RVD & AVD) by Murakawa and Jin [10] revealed that the RVD operation is more effective at the increment of critical speed by about 10 times than that of the AVD position. Suh et al. [11] found that the ultrasonic cold forging technology causes improvement in the mechanical properties of tool steel and so, leads to enhancement at the service time of trimming knives in a cold rolling process. The application of ultrasonic vibration on the equal channel

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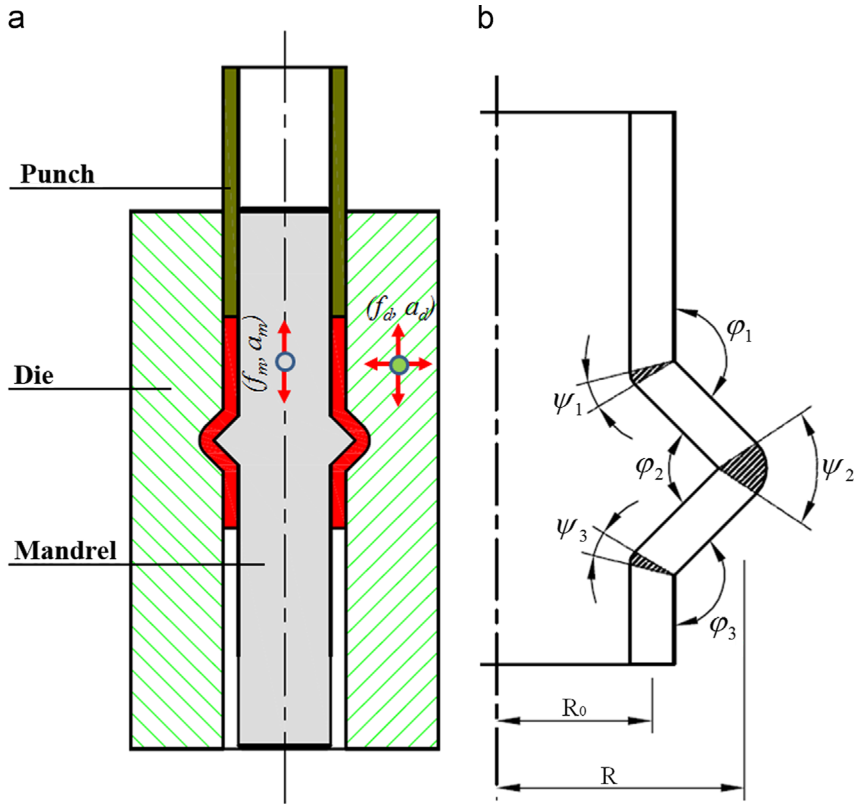

Fig. 1. (a) Schematic illustration of the TCAP process with ultrasonic vibration directions and (b) TCAP process parameters.

angular pressing (ECAP) method by Djavanroodi et al. [13] clarified that more reduction in the required forming load is obtained by increasing vibration amplitude, vibration frequency, friction factor, billet length and die channel angle. Also, vibration amplitude has more influence than frequency on the punch force reduction.

Recently, tubular channel angular pressing (TCAP) method as an effective SPD process based on the ECAP process has been proposed and experimented by the authors for imposing intense plastic strain to refine tube-shaped specimens [14–16]. The principle of TCAP process is shown in Fig. 1. At the start of the process, the tube is put into the gap between the mandrel and die. Then, the hollow-shaped cylindrical punch is positioned on the upper surface of the tube in the gap between the dies. Afterwards, the tube material is extruded by the punch into the tubular angular channel with three axisymmetric shear zones as can be seen in Fig. 1b. By considering that the cross-section of the TCAPed tube remains unchanged, this process can be repeated as many times as necessary to impose the desired plastic strain on the material [14]. To improve the efficiency of this process, it seems that the reduction of required punch force is necessary by applying ultrasonic vibration. No attempts have been made to study the influence of ultrasonic vibration on the TCAP process. So, the authors have confined the research to apply ultrasonic vibration technique on the TCAP method to investigate the deformation behavior and required pressing force. By considering that the full analysis of applied ultrasonic vibration is not feasible during the TCAP process because of the occurrence of ultrasonic wave at high speed, finite element modeling by applying of explicit analysis procedure has been utilized for this aim.

2. FEM procedures

Commercial FEM code ABAQUS/Explicit software was applied to perform the numerical simulation of ultrasonic vibration TCAP process in order to investigate strain behavior of deformed material and also required punch force magnitude. Due to symmetry, an axisymmetric modeling was carried out and an axisymmetric four node element (CAX4R) was employed to model the tube-shaped material. Tube-formed commercially pure copper was prepared with the thickness of 2.5 mm and a length of 40 mm. Compression test was done on the annealed CP copper as a test material at room temperature according to the ASTM E9-09 with a strain rate of $1 \times 10^{-5}\,s^{-1}$ and then, the true stress–strain relationship was written using Hollomon equation as $\sigma = 180\varepsilon^{0.1}$ to anticipate stresses at larger strains for importing them to the software [17]. The elastic properties of Cu sample and also, the process parameters are listed in Table 1. The die and punch were modeled as analytical rigid parts. The coulomb friction and penalty method were considered to model the contact between the die and the specimen and also, the friction coefficient was assumed to be 0.05 [18]. In addition, the constant punch speed was equal to 5 mm/min as the same as experimental work. To accommodate predetermined large deformation and prevent mesh failure during simulation, adaptive meshing, mass scaling and automatic re-meshing were employed. The arbitrary Lagrangian–Eulerian (ALE) adaptive meshing maintains a high quality mesh during the SPD process by allowing the mesh to move independently with respect to the underlying material. A mesh sensitivity diagram was attained and then, the optimum element size was found to be about 0.4 mm.

At first, verification of numerical procedure was carried out based on the magnitude of required punch load to press CP copper tube after one pass of the conventional TCAP process. After confirmation, TCAP process has been equipped with the ultrasonic vibration set-up at the FEM and then, the effects of ultrasonic vibration parameter (amplitude) have been investigated on the strain behavior and required pressing force of deformed tube-shaped specimen. By regarding previous study [13] which indicated that that UV amplitude has more