Ultrasonic assisted tubular channel angular pressing process

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ARTICLE INFO

Article history:
Received 2 November 2013
Received in revised form 20 January 2014
Accepted 23 January 2014
Available online 30 January 2014

Keywords:
TCAP
UV
FEM
Strain behavior
Pressing force

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...
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 regarding previous study [13] which indicated that UV amplitude has more influence on the punch force reduction, 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 regarding previous study [13] which indicated that UV amplitude has more

2. FEM procedures

Commercial FEM code ABAOUS/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 $\sigma = 180 \varepsilon^{0.3}$ 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 applying of explicit analysis procedure has been utilized for this aim.
influence than frequency on the force reduction, various vibration amplitudes have been simulated and the magnitude of frequency has been kept constant. For this aim, the frequency of UV has been considered to be 20 KHz according to the most recent experimental and numerical studies [4,5,13] and the vibration amplitudes have been altered to 0.1, 1, 10, 15, 20, 25, and 30 μm for both the axial and radial directions while all the other parameters have been kept constant during FEM operations. It can be said that 17 simulations have been done to survey the effects of UV amplitude on the strain behavior and required load of TCAPed tube specimen. The strain contour of the tube sample after one pass of conventional (without ultrasonic vibration) TCAP process has been shown in Fig. 2.

3. Experimental procedure

Commercially pure copper tube with the outer diameter of 20 mm, thickness of 2.5 mm and a length of 40 mm as a test material was prepared for this research. Before TCAP process, Cu tube specimen was annealed at the 550 °C for 2 h and then cooled slowly in the furnace to room temperature. TCAP die was designed and manufactured from the hot worked tool steel and then hardened to 55 HRC. The die channel angles of \( \phi_1, \phi_2 \) and \( \phi_3 \) were equal to 135°, 90° and 135°, respectively. Also, the inner corner angles (\( \psi_1 \) and \( \psi_2 \)) and outer corner angle (\( \psi_3 \)) of die were the same as 0°, 0° and 90°, respectively. TCAP operation was carried out with a hydraulic press under the pressing rate of 5 mm/min at the ambient temperature. The hydraulic press, TCAP die set-up and the tube sample during one pass process are shown in Fig. 3. Furthermore, molybdenum disulfide (MoS2) was utilized as a lubricant to reduce frictional effects between the copper tube surfaces and inner surface of the die channels.

4. Results and discussion

To verify numerical work, the results of simulation for the conventional TCAP die set-up have been compared with experiments. For this aim, the required pressing force curve has been recorded in the laboratory and compared with the model as can be seen in Fig. 4. The magnitudes of required punch load at the peak position achieved by the experimental and simulated work are about 365 KN and 338 KN, respectively. This means that about 8% inconsistency has been observed between the experimental and the numerical results which is acceptable for all practical purposes. It can be also found that there is a good agreement between the trend of both numerical and experimental force curves.

Fig. 5 represents the influence of various UV amplitudes on the effective strain (ES) magnitudes along the path as can be pointed out in Fig. 2. This path has been located at the 14 mm of the exit channel. It should be noted that the magnitude of frequency in all simulations has been considered to be 20 KHz. Also, the standard deviation (SD) of effective strain magnitude achieved by all sample elements along the path for various simulated conditions has been shown in Fig. 6. On the other hand, lower values for the SD indicates better strain distribution homogeneity for the TCAPed specimen.

As can be seen, the vibration amplitude value has considerable effects on both ES and SD magnitudes of TCAPed work-piece. In the case of the lowest amplitude value (a=0.1 μm) in both axial and radial directions, the magnitudes of ES and SD are (2% and −2%) and (5% and −3%) more than conventional condition, respectively. It means that although the value of imposed effective strain is increased, more homogeneous strain distribution is
obtained by employing UV with the $d=0.1 \mu m$. By increasing the amplitude value up to 30 $\mu m$, it can be observed that the material with high magnitude of imposed ES with better strain distribution can be obtained. For example, about 59% and 62% increments at the effective strain value and also, approximately 31% and 36% enhancement at the strain distribution uniformity have been achieved after imposing ultrasonic vibration with the amplitude of 30 $\mu m$ for axial and radial directions in comparison with the conventional TCAP process. So, higher strength copper tube with isotropic characteristic will be obtained by utilizing a UV technique in both transversal and longitudinal directions. Hence, it can be concluded that addition of amplitude magnitude leads to fabrication of tube specimen with higher effective strain and better strain distribution homogeneity.

The other important aspect of this technique is the influence of axial and radial directions of UV on the ES and SD values. By regarding Figs. 5 and 6, it can be found that radial vibration of outer TCAP die leads to higher ES value with better strain dispersal homogeneity as compared to the axial vibration when the same amplitude magnitude is considered. For example, about 3.6% and 4.4% improvement in the ES value and also, approximately 5.8% and 7.3% reductions at the SD magnitude have been attained by using the radial directional ultrasonic vibration as compared to axial UV of outer die for the amplitude magnitudes of 10 $\mu m$ and 20 $\mu m$, respectively.

The other advantage of imposing UV technique on the TCAP process is the complete filling of material in the die. Fig. 7 displays the deformed shape of TCAPed specimens after one pass process for conventional and UV circumstances. It can be observed, there are two distinctive regions in the conventional condition in which the sample does not fully fill TCAP die. In other words, two gaps appear by using conventional method. These two areas or gaps have been distinguished in Fig. 2 and also, in Fig. 7a where one is beside the inner die when the material exits the shear parts of the TCAP process (zone 1) and the other is near the outer side of the exit channel (zone 2). By considering simulated results, it can be observed that smaller or no gaps will be visible in the TCAP die by utilizing ultrasonic vibration. Employing ultrasonic vibration with the amplitude of 1 $\mu m$ to the TCAP die leads to disappearance of gap in zone 2 and also, smaller gap in zone 1. By increasing amplitude magnitude, the gap of zone 1 will be diminished as can be seen in Fig. 7(d) and (e). Furthermore to eliminate these two gap zones, the effect of radial direction of ultrasonic vibration is a little more than axial one. Hence, it can be concluded that the optimum conditions for pressing material with the ultrasonic assisted TCAP process from the strain behavior point of view are employing radial directional UV rather than axial one and also, using higher magnitude for vibration amplitude. In other words, higher effective strain value, better strain distribution uniformity and no gap zones can be achieved for the TCAPed Cu tube if radial
directional ultrasonic vibration with higher vibration amplitude has been applied.

The other prominent advantage of imposing ultrasonic vibration to this novel SPD method is the reduction of required pressing force as it was mentioned for various metal forming processes in literature survey. Fig. 8 represents the average required punch loads for pressing of pure copper sample during one pass of the TCAP process with and without ultrasonic vibrations. By regarding Fig. 8, it can be found that lower required force is needed to press the tube sample with the TCAP method by using UV. Also, increment of amplitude value leads to more reduction in the RF magnitude. In addition, the effect of radial directional vibration is more significant than axial one when the same amplitude magnitude has been considered. The result of Ref. [10] is in good agreement with this conclusion. Furthermore, the difference in the required punch loads of axial and radial directions with the same amplitude value has been grown by increasing vibration amplitude magnitude.

For example, about 61% and 90% reductions in the RF value has been respectively attained by using axial and radial directional ultrasonic vibration of die with the amplitude of 30 μm as compared to conventional state. By comparing the investigation of Djavanroodi et al. [13], it can be concluded that application of UV on die is much better than punch because of more reduction in the RF value. On the other hand, there are approximately 34% and 75% differences in the required pressing load of axial and radial directions for the (A-10 and R-10) and (A-25 and R-25) conditions respectively. These indicate that the distinction of RF value between axial and radial directional ultrasonic vibration with the same amplitude value will be increased by adding amplitude. This matter has been clearly shown in Fig. 9. Also, it is interesting to note that the peak point of required pressing force curves (Fig. 9) have been diminished by applying UV especially for the radial directional vibration as compared to the corresponding axial one because of more reduction in the friction force produced during TCAP process.

As mentioned above, TCAP process assisted by the ultrasonic vibration technique results in considerable decrease in the processing load. This may be attributed to the friction force reduction because of decreasing of the contact surface between the tube sample and the die. It means that the actual contact time between the die and sample was diminished. On the other hand, as is known, radial directional UV leads to more decreasing of the RF value as compared to the axial one with the same amplitude value, i.e. the frictional force is minimized at the contact surface by utilizing of radial UV instead of axial one.

To study the effect of ultrasonic vibration of mandrel on the strain behavior and required pressing load, two extra simulations have been done. The radial UV of the mandrel is not possible in the experiment, so only axial UV of mandrel with the amplitudes of 0.1 μm and 30 μm has been carried out to compare with the corresponding conditions when TCAP die is vibrated. Table 2 lists the magnitudes of ES, SD and RF for the axial ultrasonic vibration of mandrel and die with the amplitudes of 0.1 and 30 μm and also, the conventional condition. It is found that better strain behavior and lower punch force has been obtained by the UV of the mandrel as compared to conventional condition. In addition, by considering the same amplitude magnitude, the results of axial UV of TCAP die is much better than mandrel one. In detail, 35% increment in the ES value and also, 4.6% and 43% reduction in the SD and RF values have been achieved by using of axial ultrasonic vibration of die instead of mandrel when both of them have been compared with the conventional TCAP process.

5. Conclusions

In this research, one of the novel severe plastic deformation methods entitling tubular channel angular pressing process has been studied equipped with the ultrasonic vibration technique. The prominent conclusions can be drawn as follows:

- Employing of ultrasonic vibration leads to the enhancement of the effective strain magnitude and strain distribution uniformity. Also, it can be found that the influence of radial vibration is greater than axial one when the same magnitude of amplitude has been considered. In addition, there is no gap between the tube sample and TCAP die by using UV technique.
- Lower required pressing force is needed by utilizing a UV technique at TCAP process. Furthermore, the effect of axial directional UV is less than radial one at the force reduction.
- The axial ultrasonic vibration of TCAP die is much more impressive than mandrel from both the strain behavior and required force points of view.

Hence, the TCAPed Cu tube sample with higher imposed effective strain, better strain distribution homogeneity and lower
required pressing load can be achieved by employing higher radial directional ultrasonic vibration amplitude of TCAP die.

Acknowledgments

The authors would like to acknowledge the University of Malaya for providing the necessary facilities and resources for this research. This research was fully funded by the Ministry of Higher Education, Malaysia with the high impact research (HIR) grant number of UM.C/625/1/HIR/MOHE/ENG/27.

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