Ultrasonic flexible microextrusion forming of ZK60 Mg alloy at room temperature

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Abstract. A novel method of ZK60 magnesium formed through ultrasonic flexible microextrusion at room temperature was developed. A self-designed apparatus was applied for the ultrasonic flexible microextrusion experiments. The results showed that the forming ability and surface quality of products was improved via ultrasonic flexible microextrusion forming method. The extrusion stress distribution could be more uniform by using ultrasonic plasticizing flexible punch, compared with rigid punch.

1. Introduction
Magnesium alloy is the lightest metal structural material which can be used at present. Especially in biomedical materials magnesium alloy has good biocompatibility and mechanical compatibility. It is ideal material for cardiovascular stents. However, magnesium alloy has dense hexagonal crystal structure, and there are few independent slip systems at room temperature, which leads to the difficulty of plastic deformation. Therefore, magnesium alloy is traditionally regarded as a kind of metal material which is difficult to plastic deformation at room temperature and has poor working performance under pressure [1].

Ultrasonic vibration is widely applied in difficult-to-deform metal forming to soften material and to increase formability. Hung et al. [2] found that the flow stress during brass microupsetting can be effectively decreased by applying ultrasonic vibration, and it’s related to the specimen dimensions. The study of Bunget and Ngaile [3] showed that ultrasonic vibration can improve surface quality and abate forming load in the aluminum microforming process. Liu et al. [4] found that ultrasonic vibration can reduce the forming force and refine the grain size from 50 μm to 100~300 nm in the experimental comparison of micro-deformation of pure copper. Shimizu et al. [5] proved that ultrasonic vibration have a significant effect on transferability of the pure copper with large grain sizes in microcoining process. Zhang et al. [6] studied the influence of nonlinear ultrasonic vibration on the deformation of stainless steel materials, and established ultrasonic parameters related to the wave velocity, frequency, wavelength and amplitude. They found that ultrasonic vibration can cause local microstructure changes and micro-plastic deformation of the material, such as twin crystal and martensite deformation.

Due to many technical problems encountered in the traditional micro-forming process, we applied the ultrasonic-assisted vibration to the micro-forming of magnesium alloy [7], and found that the deformation load can be greatly reduced, which in favor of raising the forming limit of material; meanwhile, the friction between the material and the die significantly abated, which improved the
surface quality of the products and reduced the damage to the micro-die. However, the problem of this method is that the positioning accuracy of the ultrasonic punch is difficult to control in the process of microextrusion because of the high frequency ultrasonic vibration acting on the punch, which leads to the uneven structure of micro-parts, such as the uneven wall thickness. Therefore, we designed a kind of ultrasonic plasticizing flexible punch microextrusion forming method, UFP (Ultrasonic Flexible Punch) microextrusion, in this study to deform magnesium alloy at room temperature, in order to find a better forming method for this material.

2. Experiment

In our study, the initial material is ZK60 wires with $\varnothing 1.2$ mm diameter. Before experiments, the initial material would be annealed in vacuum at 430 °C for 8 h. Then the material were cut into cylindrical specimens at a ratio of height to diameter of 1.5. Ethylene Vinyl Acetate (EVA) powder was used as flexible punch material.

Ultrasonic plasticizing flexible punch microextrusion experiments were carried out on a self-designed device (Fig. 1). The ultrasonic part, which is composed of ultrasonic generator (20 kHz, 2 kW, 42 $\mu$m for maximum amplitude), transducer and punch, was fixed on a Zwick Z050 tensile machine. The ultrasonic generator transmits the sinusoidal wave signal to the transducer, which converts the electric energy into mechanical vibration. The horn punch connected with the transducer can ensure the uniform distribution of longitudinal mechanical vibration wave. Considering the stroke of microextrusion parts and the existing conditions in our laboratory, the extrusion speed $v \leq 1$ mm·s$^{-1}$.

In experiment, the diameters before and after extrusion (mm) is $\varnothing 1.2/0.5$, the ultrasonic vibration amplitude ($A$) were 0, 18, 24 and 27 $\mu$m, respectively. And 0 $\mu$m corresponds to the extrusion without ultrasonic vibration.

3. Experiment results and analysis

Figure 2 shows the UFP die and extruded micro pins. It can be seen that the thermal effect of ultrasonic vibration causes the powder of EVA to be plasticized into a semi-solid viscous state, forming the flexible extrusion punch. When the extrusion completed and the ultrasonic vibration stopped, the EVA material was quickly solidified, and had no adhesion with the surface of metal parts. Therefore, it’s easy to disconnect from the surface of the workpiece, and the surface quality of the extruded micro pins are fine. In addition, the UFP method has good sealing performance. As can be seen from Figure 2, there is basically no leakage in viscous state.
From the comparative diagrams of ZK60 magnesium alloy micro-pins (Figure 3, inside green circle) obtained by (a) conventional microextrusion method, (b) ordinary ultrasonic assisted vibration microextrusion method (rigid punch) and (c) UFP microextrusion method (the maximum pressure was 100 MPa), respectively, it can be seen that micro-pins extruded by UFP method have better forming ability, and the deformation is more uniform.

Under the maximum pressure of 100 MPa, make a comparison between the two cup-like workpieces (Figure 4) gained by ordinary ultrasonic assisted vibration microextrusion method and UFP microextrusion method, respectively, we found that the cup-like workpieces extruded by UFP method have better flatness of cup bottom, and the forming depth is deeper, which indicated that the flexible punch is beneficial to the positioning of the ultrasonic punch. Although the flexible punch absorbs some vibration energy, it has little effect on the whole forming ability.

Figure 2. UFP die and extruded micropin.

Figure 3. ZK60 magnesium alloy micro-pins obtained by (a) conventional microextrusion method, (b) ultrasonic assisted vibration microextrusion method \((A=27 \, \mu m)\), and (c) UFP microextrusion method \((A=27 \, \mu m)\).

Figure 4. ZK60 magnesium alloy tubular cup-like workpieces gained by (a) ordinary ultrasonic assisted vibration microextrusion method \((A=18 \, \mu m)\), flatness of cup bottom is bad, forming depth is 1600 \(\mu m\)), and (b) UFP microextrusion method \((A=18 \, \mu m)\), flatness of cup bottom is better, forming depth is 1678 \(\mu m\)).
The curve of extrusion stress to displacement of ZK60 micropins with diameters of 0.5 mm under different ultrasonic vibration amplitude is shown in Figure 5. It is found that the extrusion stress of UFP method is smaller than ordinary ultrasonic assisted vibration microextrusion, which phenomenon is more obvious when the amplitude is 18 μm.

**Figure 5.** Curve of extrusion stress to displacement of ZK60 micropins (maximum displacement is 1.8 mm).

4. Simulation
The finite element analysis (FEM) software ABAQUS was used to simulate the extrusion process. An axisymmetric model was used because the sample is cylindrical. The model is shown in Figure 6, which mainly includes punch, die, flexible punch of EVA and sample ZK60 Mg alloy. The rigid punch and die were set to analytic rigid body owing to their deformation is tiny and negligible during the experiment. The EVA material was regarded as a porous and deformable continuum medium in finite element analysis. Ultrasonic loading was achieved by adding a sinusoidal continuum medium in finite element analysis. The type of mesh was CAX4R.

**Figure 6.** The model of finite element analysis.
From the simulation results (Figure 7), it can be seen that the stress of the specimen is mainly concentrated near the extrusion hole, that is, the region where the deformation is most severe, during the deformation process. The extrusion length of the sample increases obviously with the increasing of ultrasonic amplitude while the large stress region (red region) decreases, which indicates that the plasticity of the sample is enhanced and the stress distribution is more uniform. In addition, compared with the stress of microextrusion using rigid punch and flexible punch, it can be found that ZK60 Mg alloy has better plasticity, longer extrusion length and larger low-stress region under the flexible punch. It is proved that the flexible punch can effectively improve the forming ability of ZK60 Mg alloy in ultrasonic vibration assisted microextrusion.
Figure 7. The simulated stress nephogram of samples of ultrasonic vibration assisted microextrusion:

Rigid punch: (a) \(A=0 \mu m\), (c) \(A=18 \mu m\), (e) \(A=24 \mu m\) and (g) \(A=18 \mu m\);

Flexible punch: (b) \(A=0 \mu m\), (d) \(A=18 \mu m\), (f) \(A=24 \mu m\) and (h) \(A=18 \mu m\).

5. Conclusion
Developed a kind of ultrasonic plasticizing flexible punch microextrusion forming method, UFP (Ultrasonic Flexible Punch) to deform magnesium alloy at room temperature, indicated that this forming method has the following advantages:

1) The microextrusion of ZK60 Mg alloy using ultrasonic plasticizing flexible punch can improve its forming ability and surface quality of products.

2) Compared with ordinary ultrasonic-assisted vibration microextrusion using rigid punch, the extrusion stress of ZK60 Mg alloy can be reduced and the deformation more uniform when the ultrasonic plasticizing flexible punch was used.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (Grant No. 51675347), the Natural Science Foundation of Guangdong province (No. 2016A030313058), the Science and Technology project of Shenzhen (No. JCYJ20160308091758179).
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