Micro-Extrusion for a Gear Shaft

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***Abstract* — A micro-extrusion machine has been developed, and micro-dies were fabricated by laser micro-machining. The extrusion process was conducted under constant pressure at constant temperatures ranging from 503 to 563K. Micro-gear shafts with gear dimensions of 0.1 in module and 800 μm in pitch circle diameter were extruded using fine grained superplastic alloy. In micro-extrusion, the tool surface roughness and lubrication influence the forming behavior and produce a threshold in punch load. The extrusion load increases with extrusion rate under constant extrusion temperature. For the results of micro-extrusion simulation with friction coefficient of 0.3 at 563K, the maximum stress is almost 90% of the maximum effective stress from the experimental result. The difference between the simulation and experimental results is due to the neglect of size effects. The micro-extrusion process was proven to successfully produce a micro-gear shaft using a fine grained superplastic alloy.*

Keywords — *Superplastic, Micro-die, Micro-extrusion, Micro-gear, Micro-forming*

I. INTRODUCTION

The emerging field of micro-forming is a miniaturization technology that has been receiving a lot of attention in industries. Micro-forming is a branch of manufacturing technology that deals with the fabrication of metallic micro-parts, such as miniature screws, connector pins, micro-shafts and micro-gears. Micro-gears are especially important actuating components that are widely used in micro-electromechanical systems device [1]. These gears can be used in micro motor, control valves, position control devices, optical adjustment devices and medical devices. Normally, micro-gears can be produced with silicon by LIGA process [2]. However this process has low productivity and high cost and there are difficulties in 3D manufacturing even though this process guarantees high precision. Thus, there is an urgent need to develop a micro-forming technology for micro-gears.

When a superplastic material with a very fine grain size is extruded at an appropriate temperature and strain rate range, it will exhibit very high ductility under low forming forces. This implies that a complex-shaped miniature component can be formed from such materials by adopting micro-forming [3-8]. Micro-patterns can be more correctly transferred to materials having smaller grains than to those having relatively larger grains.

In this study, we investigated the feasibility of micro-extrusion for producing cost effective micro-gear shaft. A micro-extrusion apparatus was developed and micro spur gear shafts were fabricated from a fine-grained Zn–22%Al eutectoid alloy. The experimental results are then compared to results from FEM simulations.

II. EXPERIMENTAL PROCEDURES

Micro-extrusion tests were carried out using a specially developed apparatus as shown in Fig. 1. The apparatus consists of a micrometer with stepping motor to produce linear motion. The frame guides a punch into the die, which is mounted in a die container with a diameter of 2.1 mm. The apparatus is equipped with a load cell (1960N capacity) to monitor the applied load. Specimen and die were heated by a small electric heater and subjected to compressive load by stepping motor. The data acquisition and control software used was ver. 8.0 LabVIEW, ver. 8.0.

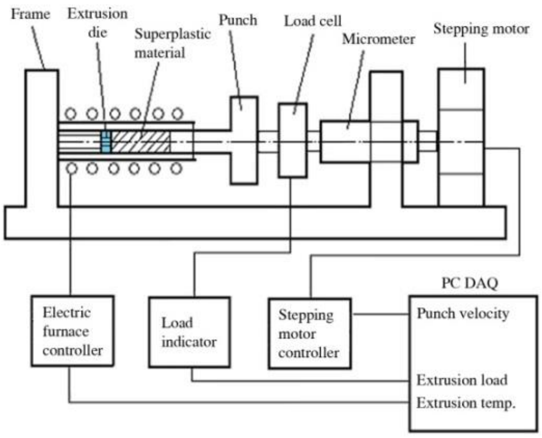


Fig. 1 Micro-extrusion system

A laser micro-machining device (Lasertech Co. Model DML40S) was used to machine the micro-die for extrusion of a micro-gear shaft. The die was machined by approximately 5μm thickness layer removal with one time laser exposure. The diameter of laser beam focus was approximately 80 μm during the machining. Therefore, the tooth width die was designed with a minimum length of 80 μm. Fig. 2 shows the machined micro-die for the spur gear; the die has eight teeth made of stainless steel 304.

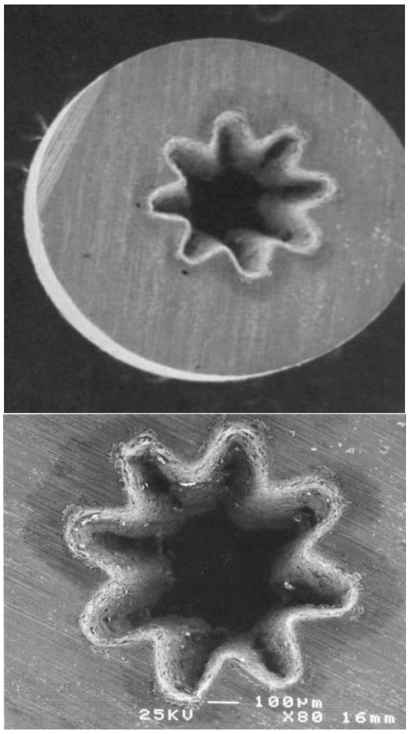


Fig. 2 Laser machined extrusion micro-die with pitch circle diameter of 800 µm

III. RESULTS AND DISCUSSIONS

Micro-forming was conducted at 503K ~ 563K with MoS_2 lubricant under compressive load of 1176 N~1862 N. Grain size of the alloy used in this work was about 2 µm, which is generally required for superplastic deformation [9]. Figure 3 shows the punch stroke as a function of time at 563K under various punch loads. This figure indicates that extrusion speed increases with increment of punch load and reaches steady state condition after short primary period. This behavior is similar to that of superplastic or creep deformation. Fig. 4 shows the steady state punch velocity as a function of punch load at various temperatures. This figure indicates that the punch velocity increases with increment of punch load and testing temperature. Especially, there is almost linear relationship between the punch velocity and the punch load.

When the punch load is lower than 1176N, as shown in Figure 4, the punch velocity reaches a value of near zero at 563K, indicating that the punch load reaches threshold load. This threshold in the punch load was caused by friction between the punch, the material and the container. In micro-forming, the tool surface roughness and lubrication generally influence the forming behavior because the amount of working energy due to friction with the tool becomes relatively large [10, 11]. As shown in Fig. 2, the laser machined surfaces of the micro-die were covered with oxides with roughness of approximately 10 to 20 µm.

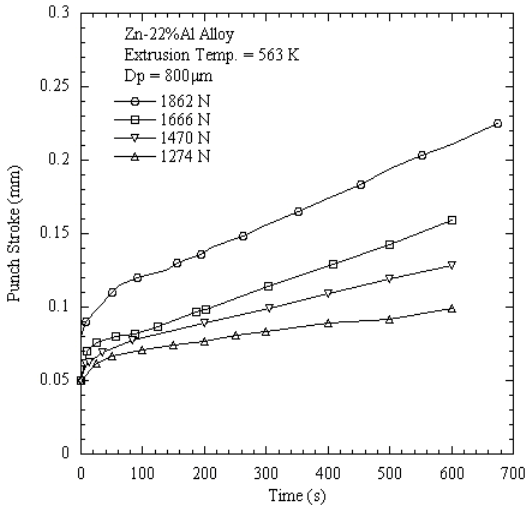


Fig. 3 Punch stroke against time for the micro-gear die at 563K

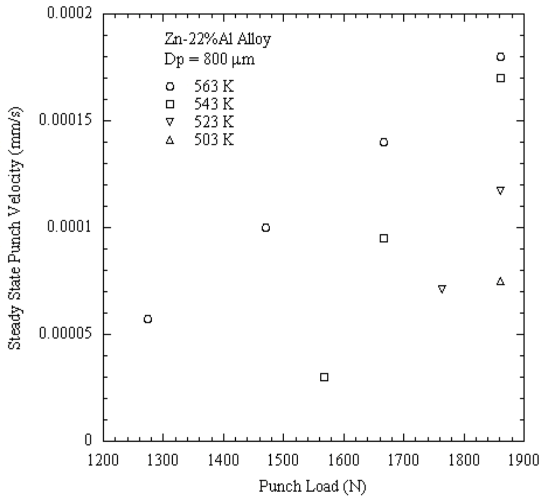


Fig. 4 Punch load against steady state punch velocity for the micro-gear die

Fig. 5 shows the threshold punch load variation for various temperatures and suggests that the threshold value decreases with increment of temperature. This is due to the fact that when the temperature increases, the creep deformation resistance of the extruding material decreases and the friction between the punch, the material and the container is constant. The cross-section area of extrusion container can be calculated as $\pi(2.1\ mm)^2/4 = 3.46\ mm^2$; the average punch pressure corresponding the threshold load of 1176N at 563K is 340 MPa. This value is very high; it takes into consideration of superplastic deformation of Zn-22%Al alloy. It can be predicted the extruding stress will occur at higher than 340 MPa during micro-extrusion process. Therefore, if we can consider the threshold stress of 340 MPa at 563K, the effective stress corresponding to the punch load of 1862N, 1666N, 1470N and 1274N are 198 141, 85 and 28 MPa, respectively.

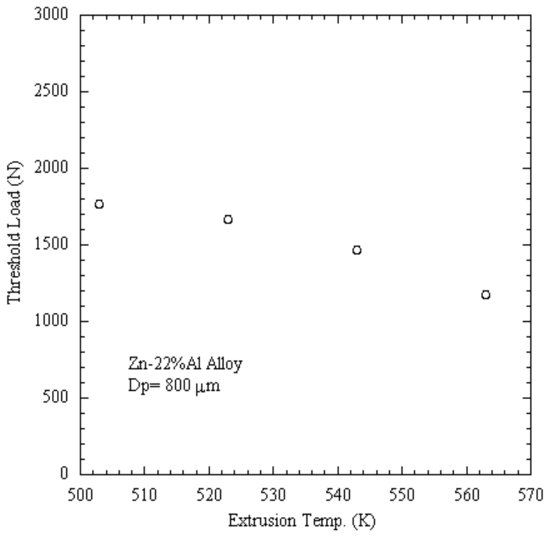
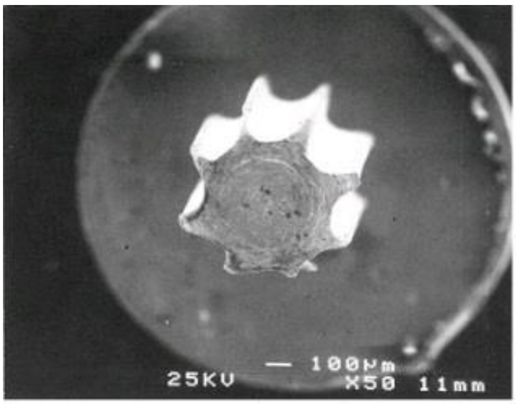


Fig. 5 Threshold punch load against extrusion temperature for the micro-gear die

Fig. 6 shows SEM micrographs of a micro-gear shaft formed using a micro-die with the Zn-22% Al alloy. Micro-forming was conducted at 563K under compressive load of 1862N. As can be seen in Fig. 7, the gear dimensions are 0.1 in module and 800 µm in pitch circle diameter. The extruded gear shaft has exact shape with a very fine and smooth surface. The extruded gear shaft has exact shape with a very fine and smooth surface. The spur gear pattern was transferred most correctly when using the Zn-22%Al superplastic alloy. This observation can be explained by the fact that micro-pattern can be correctly transferred to the materials having small grains. Therefore, the micro-extrusion process has been found to be suitable technology for producing a micro-gear shaft from a fine grained superplastic Zn-22%Al alloy.



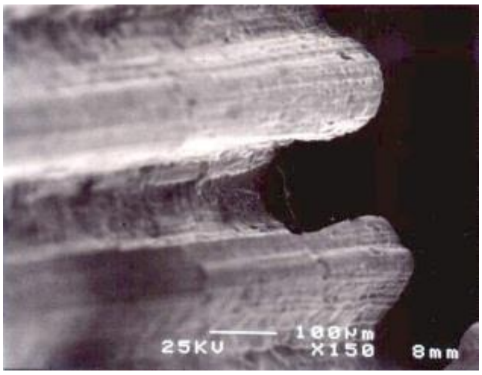


Fig. 6 SEM images of an extruded micro-gear shaft with a length of about 3.2 mm

Inspire Extrude Metal software was used to simulate the extrusion process to explain the experiment results. To simulate these extrusion, flow stress data for the Zn-22%Al alloy were obtained from a compression test. To obtain the true stress-strain curve, compressive tests on Zn-22%Al alloy billet with a diameter of 2.0 mm and length of 5.0 mm were conducted at 563K under a constant compressive speed of 1 mm/minute, as shown in Fig. 7. A plastic material model was assigned to the billet, and a rigid model was assigned to the die and punch. A finer mesh was used in regions involving localized deformation. The meshes for the extrusion analysis model were composed of 212,167 elements, respectively. The minimum size of the elements was 0.04 mm. The billet was modeled using the same size as was used in the compressive test, with a length of 5.0 mm and a diameter of 2.0 mm. The extrusion analysis model, as shown in Fig. 8 was used to run several simulations of the extrusion process at different values of friction between the die and the billet at punch velocity of 0.015 mm/s. The friction coefficient µ was set to 0.1, 0.2 and 0.3 for the extrusion.

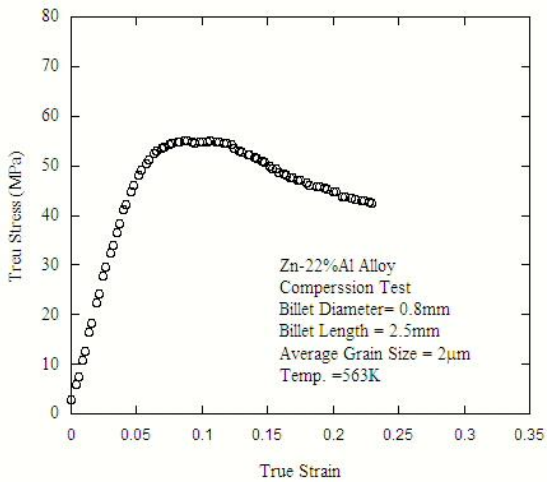


Fig. 7 True stress versus true strain curve for Zn-22%Al alloy at 563K

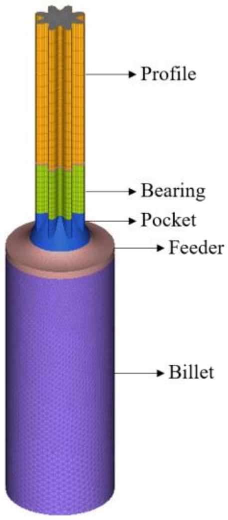


Fig. 8 FEM model for the micro-extrusion

Fig. 9 shows the simulation results for punch load and displacement at various friction coefficients for the extrusion analysis model. From the results, as the punch extrudes a billet, the applied load exhibits its peak value and decreases gradually; it then increases to the end of the extrusion. The maximum applied punch load for the full model was found to be 2084N with the coefficient of friction of 0.3, which is higher than that of the experimental result of 1862N. In addition, when the coefficients of friction were 0.2 and 0.1, the maximum applied punch loads were 1824N and 1659N, respectively, which indicates that the applied load increases as the friction coefficient is high. In real micro-extrusion, there are large effects stemming from grain size and from the orientation of the billet, from the roughness of the billet, from the die and the die container, and from other parameters. Considering these effects, the analysis should be performed to reduce the difference between the simulation and experimental results. Fig. 10 shows the results of micro-extrusion with friction coefficient of 0.3 at 563K. From the result, the maximum stress was found to be 177.6 MPa. This value is almost 90% of the maximum effective stress (=198 MPa) of the experimental result, taking into consideration the threshold stress.

The microstructure of the material and the surface condition are invariant when scaling down the dimensions from the conventional process to micro-forming processes. The ratios between the dimensions of a part to the parameters of the microstructure or to the surface change with miniaturization. This is the so-called general size effect [11]. And, there is influence of the miniaturization on the flow stress. The decrease of flow stress can be explained by so-called surface layer model [11], which is based on the fact that on small scales a material cannot be considered as a homogeneous continuum. For micro-parts, the share of grains representing the surface layer becomes high compared to the share of grains that are surrounded entirely by other grains. The friction coefficient of a miniaturized specimen was larger than that of a conventional specimen. A larger friction coefficient increased the friction force, and caused a corresponding increase in the extrusion force. These are the reason for the difference between the experimental values and the FE predicted ones. Therefore, it is necessary to consider these size effects for accurate simulation of micro-forming process.

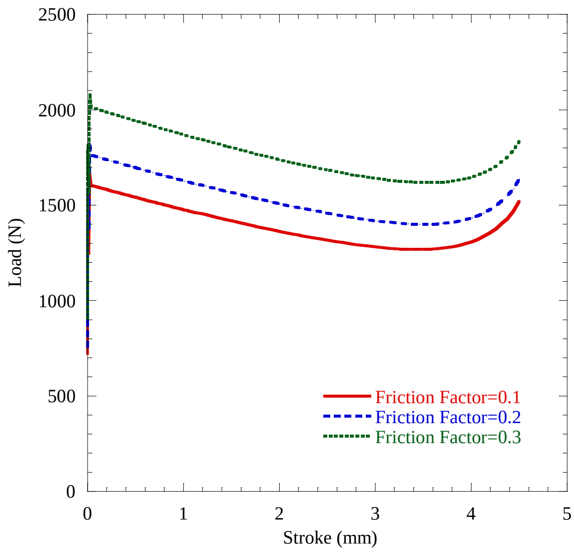


Fig. 9 Load-stroke curves of micro-extrusion under punching speed of 0.015 mm/s at 563K

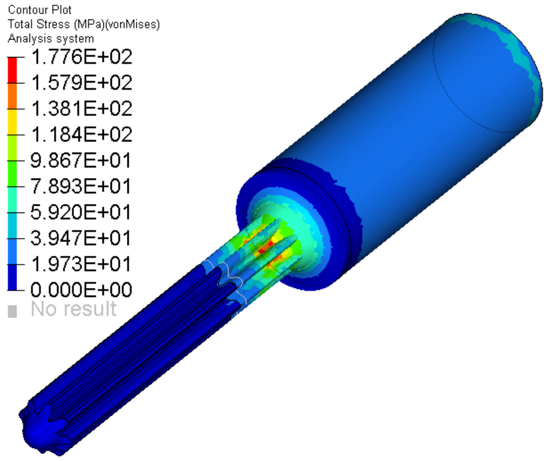


Fig. 10 Stress distribution of the extruded billet at μ=0.3 and T = 563K

IV. CONCLUSION

A superplastic backward extrusion machine was developed and laser micro-machining was employed to fabricate micro-dies. Micro-gear shafts with gear dimensions of 0.1 in module and 800 µm in pitch circle diameter were extruded using fine grained superplastic alloy. The extrusion load increased with extrusion rate under constant extrusion temperature. There was a small instantaneous stroke on application of the load; then, the applied load tended to decrease gradually. Then, the rate reached a steady state and increased after a certain period. In micro-extrusion, the tool surface roughness and lubrication influence the forming behavior and produce a threshold in punch load. There is small difference between the simulation and experimental results due to size effects. It is necessary to consider the size effects for accurate simulation of micro-forming process. The micro-extrusion process was proven to successfully produce a micro-gear shaft using a fine grained superplastic Zn-22%Al alloy.

ACKNOWLEDGMENT

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