Finite element analysis and die design of heading processes of magnesium alloy screws

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Abstract. This study is to develop related manufacturing technologies of LZ91 magnesium alloy M6 screws. Firstly, a warm heading process composed of three stages is proposed. The material flow pattern of the billet inside the die is analyzed using the finite element analyses. The effects of the friction factor, die speed and forming temperature on the heading load are discussed. The effects of the stroke at the first stage on the formability at the second stage are also discussed. Finally, warm heading experiments are conducted using a self-designed die set and a lubricant of MoS₂. The experimental values of heading load and product shapes and dimensions are compared with the simulation results to verify the validity of the finite element models and the proposed warm heading procedures.

1. Introduction
Magnesium (Mg) alloys sheets or tubes have been widely used in 3C products, especially in notebooks and flash drives, for lightweight and other excellent material properties, such as electro-magnetic shielding and recycling, etc. However, due to the HCP structure, magnesium alloys have very poor formability at room temperature. As a result, magnesium parts are usually manufactured at elevated temperatures.

Concerning head forging researches, forging die geometries are important factors for obtaining sound products without any defects. Gontarz et al. [1] presented a new forming process of screw spikes. They used the finite volume method (FVM) and finite element method (FEM) to discuss the material flow in the screw spike head forming process. Experiments with lead metal were also conducted to verify the numerical values of heading forces and flow kinematics. Pater et al. [2] developed a new thread rolling technology for sleeper fixing screws by means of two flat wedges provided with special grooves. The numerical simulation results of thread rolling process using finite volumes method (FVM) and finite element method (FEM) were compared with the experimental test results with commercial lead metal. Lin et al. [3] applied CAE (Computer Aided Engineering) combined with finite element simulation to micro screws thread rolling process design to shorten the testing time of a new product design process. Yoshida [4] conducted cold drawing and warm heading on a magnesium alloy to produce a micro screw. So far, most screws are made by carbon steels, stainless steels or aluminum alloys. Few works are involved in the forming process of magnesium screws. The forming technology, such as the influence of the forming temperature, forming speed, etc., has not been established.
2. Finite element simulations of warm heading process

A finite element code “DEFORM 3D” is used to analyze the plastic flow pattern of the magnesium alloy LZ91 during the heading process of a screw. The flow stresses of LZ91 at different strain rates and temperatures obtained by compression tests are shown in Fig. 1. When the temperatures are raised over 250°C, the flow stresses will become smaller and the strain hardening regions will become shorter at each strain rate.

The whole heading process is divided into three stages: (1) shaft extrusion, used to obtain a shaft for the subsequent threading process, (2) head forging, used to obtain outer geometries of the head, and (3) hole forging, used to obtain a hexagonal inner hole. The schematics of these three stages are shown in Fig. 2. The left and right halves denote the configurations between the die and billet before and after forming, respectively. In the shaft extrusion process shown in Fig. 2(a), a billet with a dimension of 6.5 mm in diameter and 18 mm in length is extruded through a die with an exit diameter of 5.2 mm and a bearing length of 0.5 mm. The detailed dimensions are shown in Fig. 2(b). In the head forging stage shown in Fig. 2(c), the bottom of the billet is in contact with by the die and its top part is compressed by an upper die. In the hole forging stage shown in Fig. 2(d), an inner punch die is used to forge out a hole with a hexagonal shape inside the head.

![Fig. 1. Flow stresses of LZ91 at different strain rates and temperatures.](image1)

![Fig. 2. Schematic of whole heading processes.](image2)
The expected shape and dimensions of the billet at the initial, intermediate and final stages are shown in Fig.3. During simulations, the dies are assumed to be rigid and the billet is rigid-plastic. The forming temperature is set as 150°C. Due to axis-symmetric, DEFORM 2D is used at the first and second stages, whereas DEFORM 3D is used at the final stage. The relevant forming conditions are summarized in Table 1. Fig. 4 shows the shape and dimensions of the dies used in each stages. Due to symmetry, only the right half parts are shown in the figures.
At the second stage of head forging process, the formed product is easily affected by the stroke at the first stage, which means the length of extruded shaft influences significantly the formed results at the second stage. The effects of the strokes of 12~13.5 mm at the first stage on the formed results after the second stage are discussed below.

Figures 5(a) and 5(b) show the mesh configurations before and after the head forging stage, respectively, with a stroke of $S_1=12$ mm at the first stage. Because the shaft length after the first stage is too short, the neck part contacts the lower die too early, the neck part material flows outward and then accumulates there. Accordingly, a hat-shaped defect occurred after the head forging stage. For a stroke of $S_1=13.5$ mm at the first stage, the mesh configurations for the initial, intermediate and final states are shown in Figs. 6(a), 6(b) and 6(c), respectively. Because the shaft length after the first stage is too long, the shaft part material flows outward to the upper surface of the lower die as shown in Fig. 6(b). Accordingly, a folding defect occurs at the side wall of the head after the second stage.

Table 1. Forming conditions of heading process used in finite element analysis.

| Software     | DEFORM-2D     |
|--------------|---------------|
| Material     | LZ91          |
| Billet dimensions | $\phi 6.5 \times 18$ [mm] |
| Speed of upper die | 1 [mm/s]     |
| Friction factor, m | 0.3          |
| Stroke $S_1$ (mm) | 12~13.5      |
| Forming temperature | 150 [°C]    |
Fig. 5 Mesh configurations during the second stage with $S_1=12$ mm at the first stage.

Fig. 6 Mesh configurations during the second stage with $S_1=13.5$ mm at the first stage.

For strokes at the first stage of $S_1=12.8\sim13$ mm, the mesh configurations for the initial, intermediate and final states are shown in Figs.7(a), 7(b) and 7(c), respectively. The shaft length after the first stage with $S_1=12.8\sim13$ mm is slightly longer, the redundant part material flows outward on the upper surface of the lower die and overlaps with the material from the neck part, which results in a small folding defect at the die corner as shown in Fig. 7(b). This folding defect is not easily found as shown in Fig. 7(c). However, this defect of a small crack usually results in fracture at the head part of the screw after long period usage.

Table 2 shows the mesh configurations after the second stage with different strokes of $S_1=12\sim13.5$ mm at the first stage. Clearly, the formed shapes depend largely on the strokes at the first stage. As the strokes are $12.0 \sim 12.4$ mm, a hat-shaped defect occurs. As the strokes are $12.5 \sim 12.7$ mm, corresponding to shaft lengths of $15.66 \sim 15.97$ mm, a sound product without defects can be obtained. As the strokes are $12.8 \sim 13$ mm, a not easily seen small folding defect occurs around the die corner. As the strokes are $13 \sim 13.5$ mm, an obvious folding defect occurs at the side wall and the die cavity cannot be filled up completely after the second stage.
3. Simulation results and discussion
The loads of the upper die for the three stages of the heading processes are shown in Fig. 8. The arc ratios of the die L/H defined in Fig. 2(b) are 2, 2.5, 3 and 3.5. At the first stage, as stroke $S=1$ mm, the front end of the billet moves to the entrance of the extrusion die. As $S=3$ mm, the front end of the billet reaches the die exit. As $S>3$ mm, the billet flows out from the die bearing part and a steady state is reached. At the second stage, the force increases monotonously with the stroke. At the third stage, as $0 < S < 1.5$ mm, the mandrel moves downward and the force increases due to the friction between the...
outer die and the billet. As 1.5 < S < 3.5 mm, the free outer surface of the billet is not in contact with the die, accordingly the force decreases slightly. As the mandrel approaches to the bottom of the inner hole, the outer surface of the billet begins to fill up the cavity of the outer die and then the force increases dramatically. The minimum heading load was obtained as the die arc ratio L/H=3. The maximum load at the first stage at a arc ratio of 2 is about 1.7 tons, whereas the maximum load at the second stage of heading process is about 2 tons. At a stroke of about 3.5 mm at the third stage, there is a rapid increase in heading loads. That is because a large amount of billet surface is in contact with the upper die surface simultaneously at that instant.

![Diagram](image)

**Fig. 8. Effects of die arc ratio on heading loads.**

The effects of die speed on loads of the upper die for the three stages of heading processes are shown in Fig. 9. The compression speeds of the upper die, V, are 1, 5, and 10 mm/s. From Fig. 9, it is known that the heading load increases with the increase of the die speed. The maximum load at the first stage at a die speed of 10 mm/s is about 1.2 tons, whereas the maximum load at the second and third stages of heading process are about 3 and 7 tons, respectively. For all the stages of heading process, the heading load increases with the die speed.

![Diagram](image)

**Fig. 9. Effects of die speed on heading loads.**

The effects of forming temperature on loads of the upper die for the three stages of the heading processes are shown in Fig. 10. The forming temperature of the billet, T, are 150, 200, and 250°C. From Fig. 10, it is known that the heading load decreases with the increase of the forming temperature.

![Diagram](image)

**Fig. 10. Effects of forming temperature on heading loads.**
The maximum load at the first stage at forming temperature of 150°C is about 1.2 tons, whereas the maximum load at forming temperature of 250°C is about 0.4 ton, one third of that at forming temperature of 150°C.

The effects of friction factor on loads of the upper die for the three stages of the heading processes are shown in Fig. 11. The friction factor at the interface of the billet and dies, m, are 0.1, 0.3, and 0.5. From Fig. 11, it is known that the heading load at the first stage increases with the increase of the friction factor, whereas the loads are not influenced greatly by the friction factor at the second and third stages.

4. Experiments of warm heading processes
The schematic of a self-developed warm heading apparatus is shown in Fig.12, where the upper die holder is coupled with a universal testing machine, which provides the power to push the upper die downwards. The upper and lower die set can be replaced with other die sets, so the experiments of shaft extrusion, head forging and hole forging stages, as shown in Figs. 2(a), 2(c) and 2(d), respectively, can be conducted using this apparatus. The forming conditions for warm heading experiments are the same as those in Table 1. MoS$_2$ was used as the lubricant.

The analytical and experimental loads for the three stages are shown in Fig.13. From the figures, it is known that the simulated heading loads considering non-isothermal are closer to the experimental results. The errors of the final loads at each stage between simulation and experimental values are smaller than 10%. The appearance of the formed products after each stage in the experiments of
heading processes is shown in Fig.14. The expected dimensions of the final product are shown in Fig.15. The comparisons of the final product dimensions between analytical and experimental results are shown in Table 3. The maximum error is about 4% occurring at the hexagonal hole length A.

![Fig.12. Schematic of self-developed warm heading apparatus.](image)

![Fig.13. Comparisons of heading loads between analytical and experimental results.](image)

![Fig.14. Appearance of the formed products after each stage in warm heading experiments.](image)
Fig.15. Expected dimensions of the final product. (Unit: mm)

Table 3. Comparisons of the final product dimensions.

| Analysis [mm] X | Experiment [mm] Y | Error [%] (Y-X)/X |
|----------------|-------------------|-------------------|
| Head diameter  | 12.36             | 12.7              | 2.75              |
| Head length    | 2.8               | 2.86              | 2.14              |
| Shaft diameter | 5.26              | 5.22              | -0.76             |
| Shaft length   | 15.7              | 15.91             | 1.34              |
| Hole dimension A | 4.64             | 4.47              | -3.66             |
| Hole dimension B | 4.02             | 4                 | -0.5              |

5. Conclusions
In this paper, simulations of warm heading processes of a LZ91 magnesium alloy screw were conducted firstly. The effects of the friction factor, die speed and forming temperature on the heading load were discussed. An experimental apparatus for heading processes was developed. Finally, warm heading experiments of LZ91 magnesium alloy screws were conducted with a lubricant of MoS₂. The experimental values were compared with the simulation results. Sound products were obtained with forming temperatures of 150°C in the heading process. The maximum error of the final product dimension was smaller than 4% occurring at the hexagonal hole length.

Acknowledgement
The authors would like to extend their thanks to the Ministry of Science and Technology of the Republic of China under Grant no. MOST 100-2221-E-110-033-MY3. The advice and financial support of MOST are greatly acknowledged.

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