Cold Drawing of Magnesium Alloy Tubes for Medical*

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Abstract
Magnesium alloy is the lightest in practical metals, and it is used for small home appliance products and automobile parts. It is also expected to be a new material for medical stents, because of its possibility of systemic absorption. But, it is known that the processing of magnesium alloy is very difficult and many magnesium alloys are hot-worked. Therefore, surface quality and strength of products and processing cost are the points when cold-plastic working of magnesium alloy is carried out. The purpose of this study is fabrication of a tube of magnesium alloy to improve stent strength and to reduce processing cost. Fineness, thinness, adequate strength and high-quality surface are required for stents of the medical tube. Therefore, firstly, plug drawing was carried out, because it was thought to be one of the methods for satisfying the requirements. But, it proved to be impossible to apply this method, because magnesium alloy is too brittle for plug drawing. Secondly, soft-metal mandrel drawing was tried. Drawing was possible, but it was difficult to extract the mandrel, because there is a possibility that the tube might break due to its high drawing stress. So, fluid-mandrel, a new method for mandrel drawing, was carried out. As a result, the fabrication of a fine and thin-walled tube for a stent became possible. And it was found that the wall-thickness of the tube was as thin as existing medical tubes. In fluid-mandrel drawing, fluid is used as mandrel. So, it is easy to extract mandrel after drawing. And it is possible to prevent tube break during drawing, because drawing stress is lower than that of soft-metal mandrel drawing.

Key words: Magnesium Alloy Tube, Cold Drawing, Fluid-Mandrel Drawing, Stent

1. Introduction

Recently, magnesium alloys are used in various fields. As good points of magnesium alloy are the smallest specific gravity in metal structure, the maximum specific intensity in metals(1), absorption and resolution in the body are possible, it is used for many products. Especially, it is expected to be a new material for stent of medical tubes(2). Currently, many stainless steels are used for stents. And it is said that the removal of those stainless stents after the treatment of the affected area is preferable. Therefore, a stent which is decomposable and absorbable in the body is requested. So, magnesium alloys have attracted attention as a solution for the request. However, magnesium alloys are inferior to stainless steels in strength and workability(3).

The purpose of this study is to fabricate a thin-walled and fine tube of magnesium alloy to improve stent strength and to reduce processing cost. Firstly, the possibility of cold fluid-mandrel drawing for magnesium alloy tube AZ31 is examined. Secondly, advantage of newly-processed fluid-mandrel cold drawing is examined. Fineness, thinness, adequate strength and high-quality surface are required for stents of medical tube. When a tube is processed by hot mandrel drawing, the wall-thickness of the tube increases, and it is not controllable(4). So newly-processed cold fluid-mandrel drawing was carried out, as the methods for satisfying the requirements. Fluid-mandrel drawing is used fluid for mandrel.
So it is easier in fluid-mandrel drawing than in mandrel drawing to extract mandrel after drawing.

2. Material and Experimental Procedure

Tubes of 7.5mm in diameter and 0.75mm in thickness of magnesium alloys AZ31 were used. Typical tube drawing methods are shown in Fig.1. And those are roughly divided into two methods. One is hollow sinking and the other is drawing with mandrel or plug. The purpose of this study is the fabrication of thin-walled fine tubes underlying of stents. Therefore, firstly, plug drawing was carried out, because it was thought to be one of the methods for fabrication of thin-walled fine tubes. After all it was found to be impossible to apply this method, because magnesium alloy is too brittle for plug drawing. Secondly, soft-metal mandrel drawing, which is kind of mandrel drawing and in which pure aluminum is used as a mandrel to prevent tube brake during processing, was carried out. Drawing was possible, but it was difficult to extract the mandrel, because there is a possibility that the tube might break due to its high drawing stress. So, its fabrication possibility by newly-processed fluid-mandrel drawing was examined. Schematic illustration of the fluid-mandrel drawing is shown in Fig.2.

Water of 0.001Pa·s viscosity and 4.3MPa⁻¹ compressibility and machine oil of 0.5 Pa·s viscosity and 7.1MPa⁻¹ compressibility are filled in a testing tube, and an aluminum plug is put at each end of the tube. Then the tube is drawn through a die. In this method, the fluid which is filled in the tube plays a roll of a mandrel, and brings the possibility of the prevention of wall-thickness increase that is likely to occur in drawing. A carbide die was used, and its die half angle was 6°. Reduction per pass (R/P) was 5%, 10% and 15%. Three kinds of lubricants, such as Resin-based lubricant, Petroleum-based lubricant and Stearin sodium-based lubricant, were used for lubrication.
The tube was annealed after every 2-pass. The annealing temperature is 573 K and the holding time is 30 minutes\(^{(7)}\)(\(^{(8)}\)). The velocity of drawing was 500mm/min. Moreover, in this study, FEM analysis was carried out to compare the mechanism of each drawing method. Work hardening diagram of annealed magnesium alloy tube for FEM analysis is shown in Fig. 3. And FEM analysis model of fluid-mandrel drawing is shown in Fig. 4. In FEM analysis for fluid-mandrel drawing, pressure which produces the wall-thickness equivalent to that of fluid-mandrel drawing was applied.

3. Results of Experiment

3.1 Cold drawing by fluid-mandrel drawing

Because of the low cold workability of magnesium alloy, many magnesium alloys are hot-worked with R/P=10–20 \%\(^{(9)}\). And cold drawing of them are barely done. Therefore, at first, the limit of cold drawing and optimum reduction per pass were examined. Fig. 5 shows the drawing limit when resin-based lubricant was used. As can be seen in Fig. 5, fluid-mandrel cold drawing is possible. However, high total reduction (Rt) was not able to be obtained, and drawing limit was around Rt=15\%. In the subsequent experiment, R/P=5 \% is fixed, which shows the highest limit of cold drawing as can be seen in Fig. 6.

3.2 Effect of lubricant on the limit of cold drawing

Optimum lubricant for cold drawing was examined to improve the workability of magnesium alloy. Three kinds of lubricant such as Resin-based, petroleum-based, and Stearin-sodium-based were prepared. Fig. 6 and Fig. 7 show the results of drawing limits and drawing stresses, when R/P=5 \% is fixed. It was possible to draw magnesium alloy up to Rt=15\%, when resin-based lubricant was used. As a result, resin-based lubricant seems to be optimum for cold drawing of magnesium alloy.
3.3 Change of thickness / diameter ratio of drawn tube

As previously described, cold hollow sinking of magnesium alloys was possible. But there is a concern that the increase of tube wall-thickness may occur and inner surface quality of the tube may deteriorate, when passes are repeated dozens of times. Therefore, thickness / diameter ratio thinned by oil-and-water fluid-mandrel drawing, and thinned by hollow sinking were examined. The results are shown in Fig. 8. 14-pass drawing and annealing after every 2-pass were given to the testing tube, under the condition that the die half angle is 6° and R/P=5%.

Cross-section pictures of the tube which were drawn at total reduction Rt=53% are shown in Fig.9. Thickness / diameter ratio increases when hollow sinking is applied, and it is acknowledged that the wall of the processed tube is thick. Meanwhile, it was found that the wall of the tube processed by fluid-mandrel drawing was also thick but thickness / diameter ratio of the tube was small. In the meanwhile, tubes with thickness / diameter ratio of 19% or less are used in medical tubes. As will be noted from Fig.8, tubes processed by fluid-mandrel drawing satisfy the requirement for the ratio. Among other things, it was found that thickness / diameter ratio of the tube processed by high-viscosity-oil fluid-mandrel drawing was low, compared to those of the tubes processed by other fluid-mandrel drawing. From these result, it became clear that a tube of which wall-thickness is as thin as existing medical tubes can be produced by fluid-mandrel drawing.

![Fig.8 Change of thickness / diameter ratio of drawn tube](image)

![Fig.9 Cross-section pictures of Rt=53% tube](image)
3.4 Change of tube inner surface roughness

The inside of a stent must be smooth to relieve a risk of reocclusion (10). Therefore, comparison of tube inner surface roughness in each drawing such as hollow sinking, mandrel drawing, and fluid-mandrel drawing was made. SEM images of inner surface roughness of tubes which are processed at Rt=53%, from 7.5mm to 3.6mm in diameter, are shown in Fig. 10. As can be seen from Fig. 11, inner surface roughness of the processed tube is gathered in a circumferential direction of the tube in accordance with the reduction of the tube outer diameter, and the degree of inner surface roughness declines. And in the case of the tube processed by hollow sinking, tube inner surface roughness can be worse. Meanwhile, in the case of the tube processed by fluid-mandrel drawing, the tube inner surface roughness is suppressed, owing to the fact that the free deformation of the fluid stuffed in the tube is constrained. Furthermore, it is acknowledged that the inner surface roughness of the tube stuffed with oil is smaller than that of the tube stuffed with water. Fluid-mandrel drawing makes it possible to lower tube inner surface roughness, and it is suitable for the fabrication of medical fine tube which requires thinness and good inner surface quality.

![Fig. 10 Rt=53% tube inner surface SEM images](image)

a) Original tube
Ra=0.31[µm]

b) Hollow sinking
Ra=0.98µm

c) Soft-metal mandrel drawing
Ra=0.45[µm]

d) Fluid-mandrel drawing (water)
Ra=0.63µm

e) Fluid-mandrel drawing (oil)
Ra=0.52[µm]

3.5 Comparison of hardness

A stent is a medical tube that is inserted into blood vessel to keep it open. Therefore, it is required to have enough strength to support a blood vessel from within (11). Hardness of tubes which were processed by each drawing such as hollow sinking, mandrel drawing, and fluid-mandrel drawing were measured at five points of each tube. Measurement points of tubes are shown in Fig. 11. The results are shown in Fig. 12. As will be noted from Fig. 12, the hardness of every tube increases, and this is attributed to the shear strain caused by cold drawing. And the hardness of a tube processed by fluid-mandrel drawing is harder than that of a tube processed by hollow sinking, and as hard as that of a tube processed by soft-metal mandrel drawing. This means that a high-strength tube can be made by fluid-mandrel drawing.
3.6 Difference of drawing stress

Drawing stress is a parameter that shows the degree of breakage. Therefore, comparison of drawing stresses in each drawing such as hollow sinking, mandrel drawing, and fluid-mandrel drawing was made. Figure 13 is the results. The figure shows that the drawing stress of fluid-mandrel drawing is lower than that of soft-metal mandrel drawing. This means that fluid-mandrel drawing is better in preventing the occurrence of a breakage or cracks than soft-metal mandrel drawing. Also, it was found that the difference of property of fluid which is used as mandrel affects on the drawing stress.

4. Results of FEM analysis

4.1 Wall-thickness change of each drawing method

Fig. 14 Change of wall-thickness by experiment and FEM analysis
Wall-thickness change in every 1 pass in each drawing method was checked by FEM analysis. Applied fluid-mandrel pressures were as follows: 4.5[MPa] for water and 5[MPa] for oil. These values are decided to generate wall-thickness equivalent to that generated by experiment. Fig. 14 shows the results. It shows the wall-thickness processed by hollow sinking increases, meanwhile the wall-thickness processed by fluid-mandrel drawing decreases. This means that the wall-thickness was controlled by the pressure inside the tube. And the wall-thickness change by experiment and that by FEM analysis are nearly identical in each drawing method. As a result, it was found that it is possible to predict wall-thickness change by FEM analysis.

4.2 Comparison of hydrostatic stress by each drawing method

It is possible to evaluate the occurrence of a tube brake during drawing by hydrostatic stress, so hydrostatic stress in every drawing method was examined by FEM. Results are shown in Fig. 15. Besides hydrostatic stress, the tube wall thickness can be calculated by FEM. As mentioned above, it is clarified that wall thickness after sinking increases due to hoop stress by applying alternated sinking. The hydrostatic stress in a tube just under a die becomes compression in every drawing method. Above all, Soft-metal mandrel drawing showed the highest compression stress, and hollow sinking showed the lowest compression stress. On the other hand, hydrostatic stress in a tube becomes tension in fluid-mandrel drawing and soft-metal mandrel drawing (see dotted-line in Fig. 15), but it is judged that this degree of tensile stress does not cause a tube brake during drawing.

Due to the stress described above, the thickest tube wall can be produced by hollow sinking and the thinnest tube wall can be produced by soft-metal mandrel drawing. And, once tensile stress on a tube surface after passing through a die becomes excessively high, the tube tends to be led to brake. So, the selection of pass reduction becomes important.

We will give consideration to the relationship between tensile stress on a tube surface and breakage of the tube after passing through a drawing die in the future.

5. Conclusion

The purpose of this study is to fabricate of a thin-walled and fine tube of magnesium alloy to improve stent strength and to reduce processing cost by fluid-mandrel cold drawing. Therefore, optimum reduction per pass and optimum lubricant for cold fluid-mandrel drawing of magnesium alloy was examined. Also, drawing stress, thickness / diameter ratio, and hardness of each tube processed by different drawing methods were compared to identify the advantages of fluid-mandrel drawing, which is a new method for tube drawing. The obtained results are summarized below.
(1) Fluid-mandrel cold drawing of magnesium alloys is possible, when reduction and lubricant are optimized. In this study, magnesium alloy tubes worked from 7.5mm to 3.6mm out diameter.

(2) The drawing stress of fluid-mandrel drawing is lower than that of soft-metal mandrel drawing. In the case of fluid-mandrel drawing, it is possible to prevent the breakage of a tube, and to pull out mandrel, or fluid, easily.

(3) In the case of hollow sinking, both inner and outer diameters shrink. However in the case of fluid-mandrel drawing, only outer diameter shrinks because of the fluid pressure from inside the tube. This means that it is possible to control the increase of thickness and then to make a thin-walled tube. In this study, a tube of 0.61mm in thickness was fabricated as thin as medical tube.

(4) In the case of fluid-mandrel drawing, fluid pressure occurs inside the tube. This fluid pressure checks free deformation and deterioration of roughness of the inside of the tube.

(5) It is acknowledged that fluid-mandrel drawing is suitable for fabrication of medical tubes. In the future, fluid-mandrel drawing will be applied to the fabrication of a tube for a stent.

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