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MODELING OF COLD DRAWING OF MAGNESIUM ALLOY WIRES AND TUBES

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Abstract

The feasibility and application of the cold drawing of magnesium alloy wires and tubes were examined by Finite Element Method (FEM) and experiments. Magnesium alloy, which is light and has high heat-radiating ability, has been attracting attention for applications, such as the body of computers, medical instruments and mobile phones. However, cold plastic working of the alloy is very difficult, so generally hot working is necessary. In this study, a technique for obtaining fine wires and tubes with high strength, quality and surface morphology by cold drawing was examined, while decreasing production cost. In addition, the shearing strain of magnesium alloy wires and tubes drawn under various drawing conditions was calculated by FEM analysis. It was clarified that cold drawing of magnesium alloy is possible.

Key words: cold drawing, magnesium alloy, wire, tube, workability

1. INTRODUCTION

Recently, magnesium alloys with various superior characteristics, such as light weight and high heat-radiating ability have attracted attention for applications in small digital electronic appliances such as laptop computers, wheelchair frames, machine frameworks, medical equipments and automobiles. However, because the crystal lattice of magnesium alloy has a hexagonal close-packed structure its cold workability is extremely poor (Conroy, 1989; Hasegawa & Nishimatsu, 2000; Japan Institute of Light Metals, 2003; Oishi et al., 2005; Okazaki et al., 2003), and magnesium alloys are generally processed by warm or hot working (Japan Institute of Light Metals, 2003; Nishimura et al., 2003; Ohwue et al., 2001; Okazaki et al., 2003; Oki & Miyamoto, 2001). In this study, in order to reduce the processing costs and to increase the strength, quality and surface characteristics of magnesium alloys, the feasibility and application of the cold drawing of magnesium alloy is examined by FEM analysis and experiments.

2. EXPERIMENTAL METHOD AND FEM MODELING OF DRAWING

2.1. Experimental method

Magnesium alloy wires (d_0 = 3.93 mm) and tubes (d_0 = 13.03 mm, t = 0.94 mm) of AZ31 were used in this study. Table 1 summarizes the chemical composition of AZ31. The surface morphology and metal structure of magnesium wires and tubes were observed using a scanning electron microscope (SEM) and an optical microscope, respectively. In the drawing experiment, we used a cemented carbide conical die, which is commercially available, with a die half-angle of 6 degrees for wires and 6 and 13 degrees for tubes. The drawing method of the tube was

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hollow sinking. One pass reduction R/P was in the range of 10-26% for wires and 5-19% for tubes. Figure 1 shows the drawing process and the definition of R/P. Resin lubricant and sodium stearate soap were used as lubricant.

Table 1. *Chemical composition of tested magnesium alloy AZ31.*

Element	Average content (wt%)
Al	3.06
Zn	0.82
Mn	0.36
Si	0.019
Mg	Bal

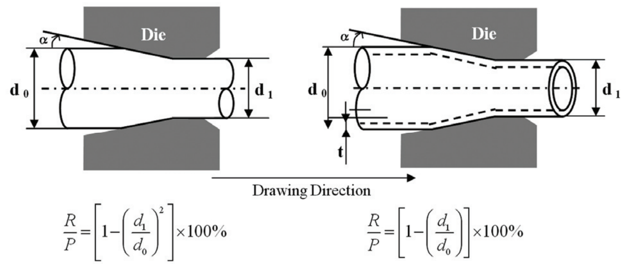


Fig. 1. *Definition of one pass reduction for wire drawing and tube sinking.*

2.2. FEM modeling of drawing of wire and tube

FEM code MSC/Marc Mentat 2008r1 was used in this study. Figure 2 shows the model used in the FEM analysis, and figure 3 shows its material constant. Coefficient of friction (μ) was set at 0.05. Moreover, the model was assumed to be axis symmetric in the FEM analysis to save calculation time. It would be possible to obtain the die pressure by the FEM analysis, if the die were assumed to be elastic-plastic (figure 4). But in this study, the die was assumed to be rigid in order to facilitate the calculation.

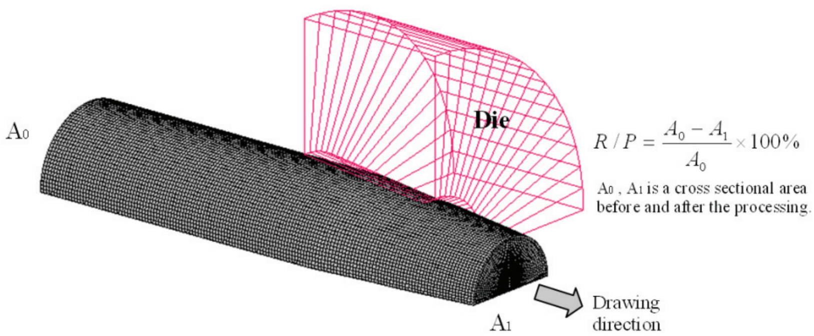


Fig. 2. *Drawing model of wire and tube.*

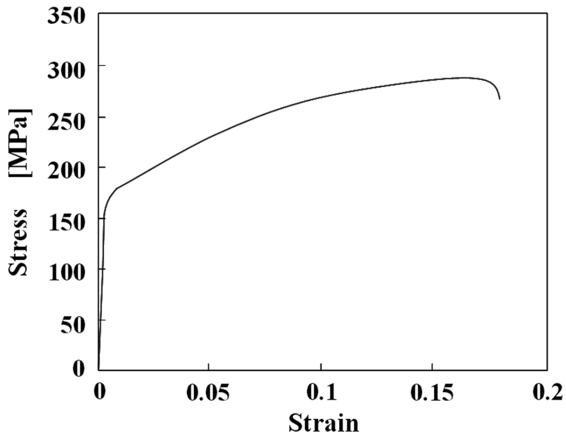


Fig. 3. *Stress-Strain curve for FEM analyses.*

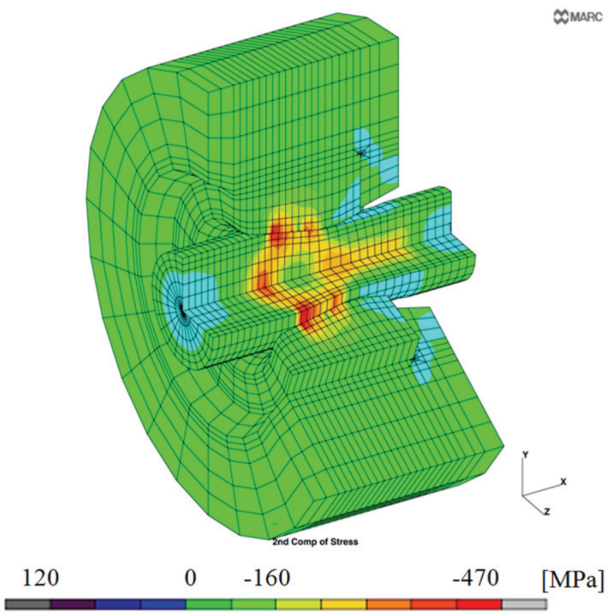


Fig. 4. *Calculated die pressure distribution during the wire drawing by FEM.*

3. RESULTS AND DISCUSSION

3.1. Feasibility of cold drawing of magnesium alloy wires

Figure 5 shows the drawing limit obtained for each pass schedule. We used a cemented carbide conical die, which is commercially available, with a die half-angle of 6 degrees and resin lubricant. Up to R/P of 25%, cold drawing of magnesium alloy AZ31 was possible; reduction of the diameter from d_0 = 3.93 mm to d_1 = 2.45 mm was also possible (Yoshida, 2004; Yoshida et al., 2002).

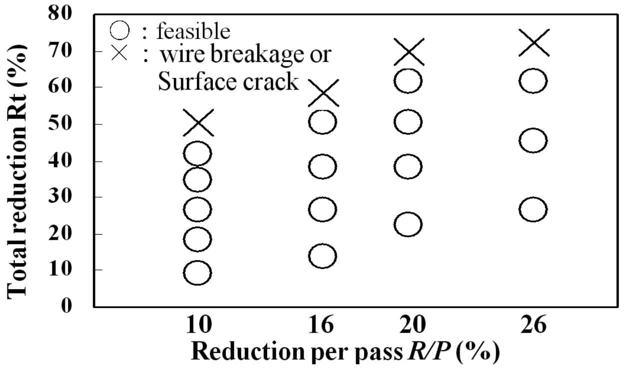


Fig. 5. *Drawing limit obtained for each pass schedule of wire.*

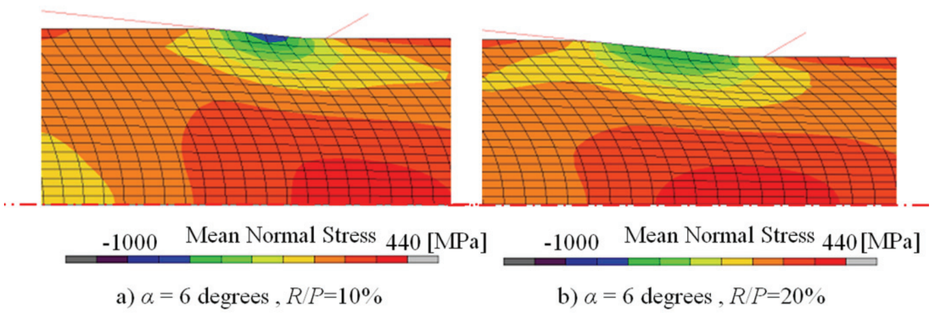


Fig. 6. *Distributions of hydrostatic stress during the wire drawing with a die half-angle of 6 degrees and R/P = 10%, 20%.*

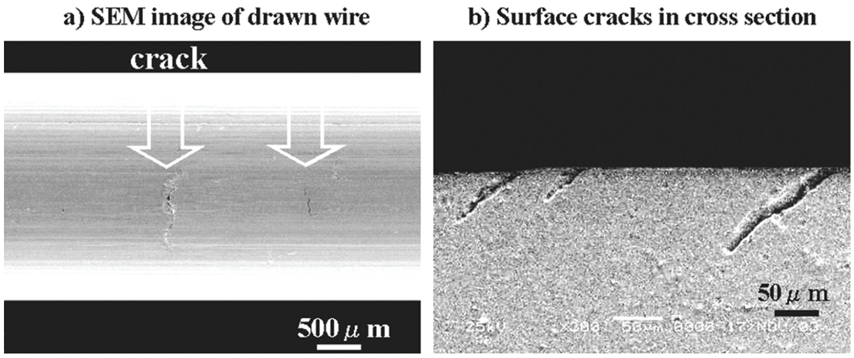


Fig. 7. *Surface crack on drawn magnesium alloy wire.*

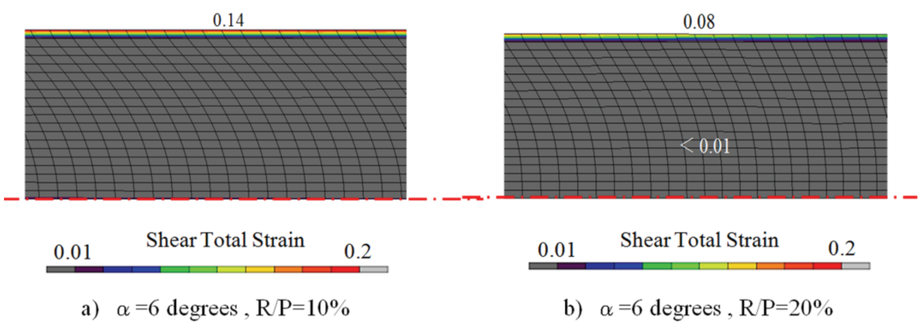


Fig. 8. *Distributions of equivalent shear strain on drawn wire by FEM.*

Hydrostatic stress distributions during wire drawing with a die half-angle of 6 degrees and *R*/*P* = 10%, 20% by FEM are shown in figure 6. Since the hydrostatic stress during the drawing is the compression, it has been judged that the cold drawing of magnesium alloy becomes possible. In the actual drawing of practical fine wires, *R*/*P* is suppressed to be as small as possible to prevent the surface crack on drawn wire and wire breakage. When *R*/*P* is low, 10%, the drawing limit of the magnesium alloy is also low.

Figure 7 shows the surface cracks on drawn magnesium alloy wire. These cracks near the wire surface are shear cracks, the cracks develop from the free surface to the 45 degree direction. Shearing deformation affects the surface crack initiation. As shown in the results by FEM (figure 8), the large equivalent shear strain is arising in the place which is close to the wire surface, also the equivalent strain becomes large, as *R*/*P* in drawing becomes smaller.

As shown in figure 9, tensile and shear deformation of the wire was dominant in drawing. In contrast, shear deformation was dominant at the surface of the wire. The drawing limit decreased as *R*/*P* decreased: the reason for this was considered to be as follows: with decreasing *R*/*P*, the shear deformation at the surface of the wire becomes large for the magnesium alloy to withstand, leading to wire cracks.

3.2. Strength of drawn wires and hardness distribution

To investigate the work hardening of drawn wires, wire samples with various total reductions (*Rt*) from 0% to 62% were prepared. Figure 10 shows the results of tensile tests of these wires. The tensile strength of wires with high *Rt* increased after working hardening. In addition, although the rupture elongation of annealed material (*Rt* = 0%) is approximately 16%, it decreased to approximately 6.8% upon repeated drawing. On the basis of these findings, the relationship between *Rt* and the mechanical characteristics of the wire material was redefined as shown in figure 11. It was found that wire material with high strength can be obtained through work hardening by cold drawing.

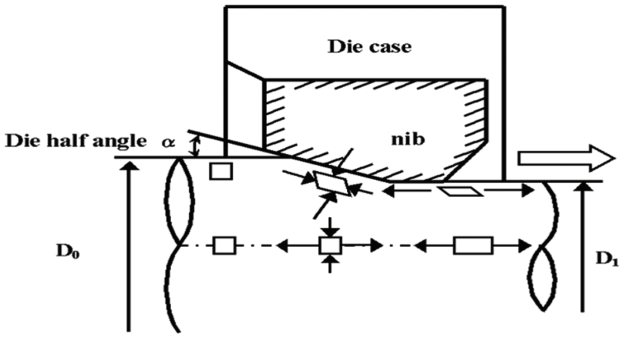


Fig. 9. *Schematic graph of material deformation during wire drawing.*

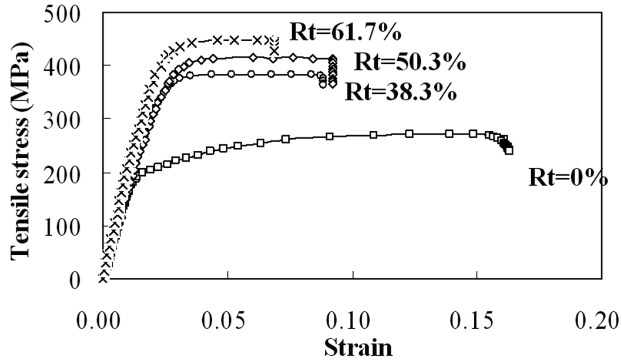


Fig. 10. *Results of tensile test of drawn magnesium alloy AZ31 wire.*

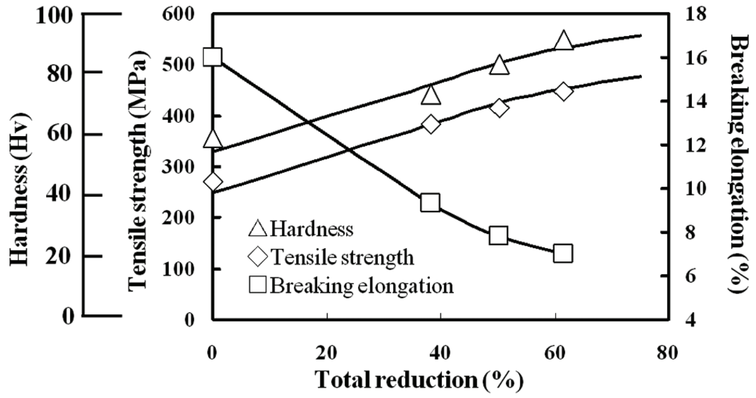


Fig. 11. *Relationship between total reduction and mechanical characteristics.*

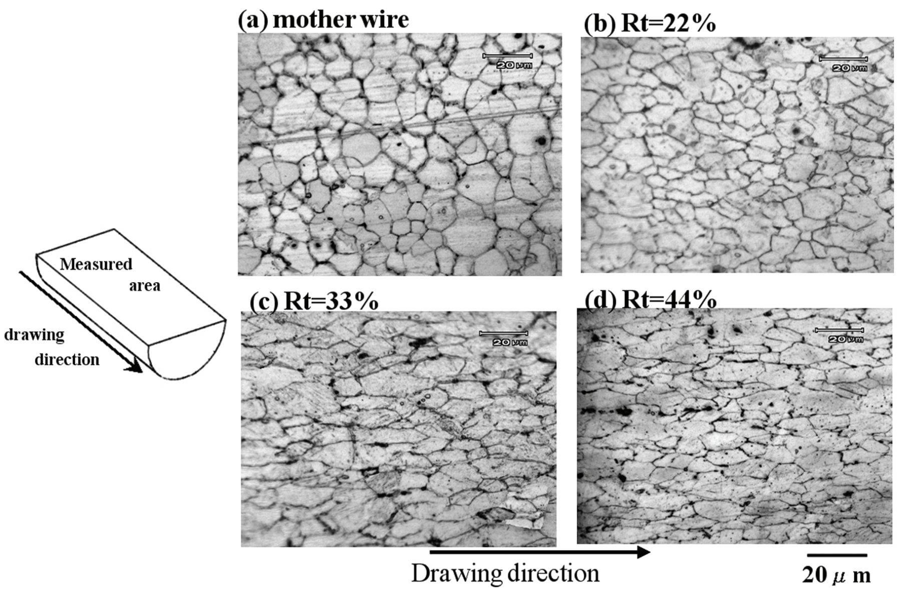


Fig. 12. *Metallographic structure of mother wire and drawn wires.*

3.3. Observation of metallic structure of drawn wire

The cross section of the drawn wire is observed to examine the change of the metallic structure due to work hardening. Figure 12 shows images of the metallic structure of wires (a) before drawing (φ2.1 mm), and after drawing at 6 degrees of die half-angle and *R*/*P* = 20% for (b) *Rt* = 22%, (c) *Rt* = 33%, and (d) *Rt* = 44%. The crystalline grains of the mother wire are large and round before drawing. After cold drawing, the wire is subjected to work hardening in the drawing direction. With increasing the number of passes, the grains are further stretched in the same direction.

3.4. Drawing limit of magnesium alloy tube during cold drawing

Figure 13 shows whether cold tube drawing is possible and the drawing limit for various R/P, when the die half-angle is 6 and 13 degrees (Yoshida & Fueki, 2006). The white circles are the results when 6-degree die half-angle was used, and the black circles are the results when 13-degree die half-angle was used. As shown in the figure, cold drawing of the magnesium alloy tube is possible until the total outer-diameter reduction ratio becomes approximately 15%. In the case of the tube drawn at *R*/*P*=15% and α = 13 degrees, the drawing limit fell compared to that of α = 6 degrees. This is because of the drawing-stress increase caused by the shortened contact length which is brought by α = 13 degrees. In other words, it is thought that the drawing limit has deteriorated. Figure 14 shows the distributions of hydrostatic stress during tube drawing at 5 passes. The condition of the outer surface of the drawn tube is good up to two passes.

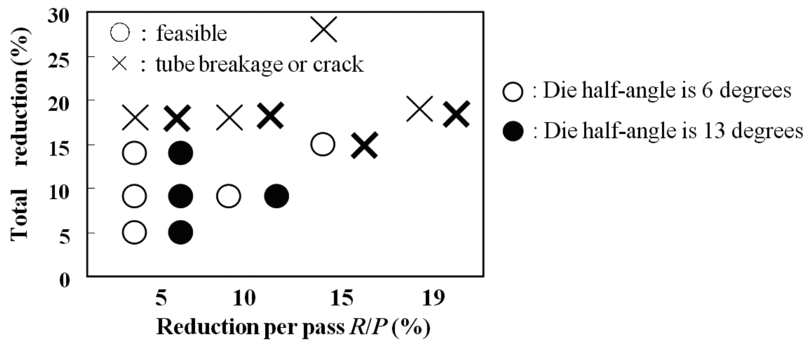


Fig. 13. *Drawing limit obtained for each pass schedule of tube*

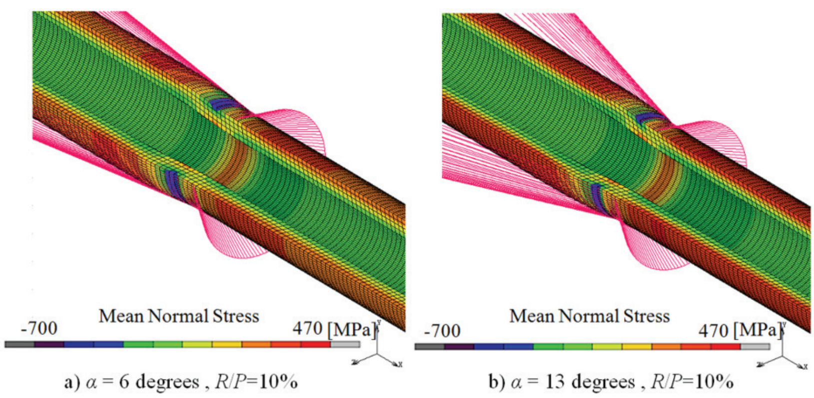
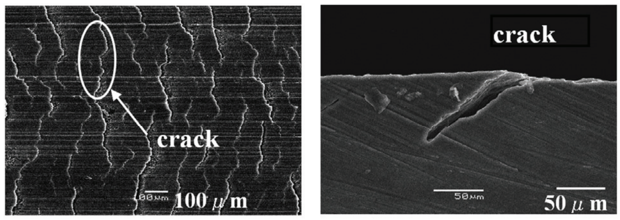


Fig. 14. *Hydrostatic stress distribution and contact length of material during tube drawing.*

However, on the surface of the tube after four passes with α = 13 degrees and R/P=10%, small flaws as shown in figure 15 are observed (Yoshida & Fueki, 2006). The observation of the tube cross section revealed that approximately 70 μm-long flaws, which are similar to shear cracks, were generated. In the subsequent drawing passes, shear cracks were generated along the direction of 45 degrees to the drawing axis, and further drawing of the tube was not possible. The shear cracks may arise because deformation of the tube during drawing leads to additional shear deformation at the tube surface.



(a) Surface crack of drawn tube (b) Surface crack on cross section

Fig. 15. *Shear crack which appeared in drawn tube surface.*

3.5. Estimation of the drawn tube wall thickness in sinking

After the application of resin lubricant, sodium stearate soap was applied over the tube as an additional lubricant, and the tube was drawn for three passes at α = 6 and 13 degrees and *R*/*P*=10%. After annealing, the obtained tube was drawn up to six passes and the wall thickness was examined experimentally and by FEM (figure 16). It was found that wall thickness increased by approximately 3%(α =13 degrees) or 6%(α = 6 degrees) for every drawing pass because of sinking. The rate of wall-thickness increase of the tube drawn at α = 6 degrees is higher than that of the tube drawn at α = 13 degrees.

Figure 17 shows the cross sections of (a) the mother tube and tubes drawn to a tube diameter of 9.45 mm at (b) α = 6 degrees and (c) α = 13 degrees. As discussed above, the cold sinking of magnesium alloy tube was found to be possible by FEM.

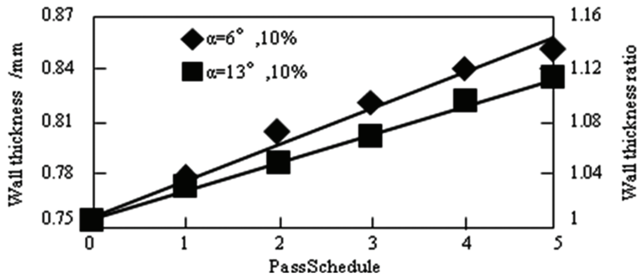


Fig. 16. Change in thickness with increasing number of passes using die half-angles as parameter.

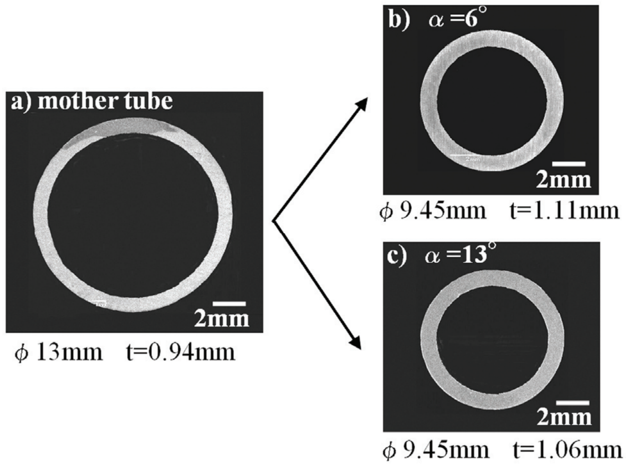


Fig. 17. Cross sections of drawn magnesium alloy tubes after 5 passes.

4. CONCLUSION

We have investigated the possibility of cold drawing of magnesium alloy AZ31 wire and tube, experimentally and by a finite element method. The obtained results are summarized below.

1. It was clarified that cold wire drawing of magnesium alloy AZ31 is possible. This is attributed to the fact that the hydrostatic stress is compressional near the surface region of deformation zone during drawing, as calculated by FEM analysis. Cracks of wire are more likely to occur, when the hydrostatic stress at the inner part of wire is tensile. So it is a key point to use a small-angle die.
2. By optimizing the drawing conditions of lubricant and die angle, drawing with a total reduction of up to approximately 60% was possible.
3. Shearing deformation which was occurred on wire surface affects the surface crack initiation.
4. Changes in material strength, hardness distribution and metallic structure of drawn wire were clarified.
5. The drawing of the tube is also possible as well as the drawing of the wire, the outer-diameter reduction ratio per pass of up to 15% is possible by cold sinking.
6. With the repetition of drawing passes, shear cracks are generated on the tube surface. In the worst case, the shear cracks develop approximately 45 degrees to the drawing direction, when lead to the rupture of the tube.

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MODELOWANIE CIĄGNIENIA NA ZIMNO DRUTÓW I RUR ZE STOPÓW MAGNEZU

Streszczenie

W artykule opisano badania nad możliwością zastosowania procesu ciągnienia na zimno dla stopów magnezu. Przeprowadzono badania doświadczalne i modelowanie metodą elementów skończonych. Stopy magnezu, który charakteryzuje się małą gęstością i wysoką zdolnością oddawania ciepła, są w centrum zainteresowania badaczy w aspekcie takich zastosowań jak komputery, narzędzia medyczne, i telefony komórkowe. Z drugiej strony, plastyczna przeróbka stopów magnezu na zimno jest bardzo trudna i przeważnie stopy te odkształcane są na gorąco. W niniejszej pracy przedstawiono wyniki badań nad technikami otrzymywania drogą ciągnienia na zimno drutów i rur o małych średnicach oraz o wysokiej wytrzymałości i dobrej jakości powierzchni, przy utrzymaniu niskich kosztów wytwarzania. Odkształcenia postaciowe w ciągnionych drutach i rurach były wyznaczane metodą elementów skończonych. Wykazano, że ciągnienie na zimno stopów magnezu jest możliwe.

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