Finite Element Simulation with Coupled Thermo-Mechanical Analysis of Superplastic Dieless Tube Drawing Considering Strain Rate Sensitivity*

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The deformation behavior in superplastic dieless tube drawing is studied numerically by the finite element method (FEM). The FEM with coupled thermo-mechanical analysis is conducted considering strain rate sensitivity to clarify the effect of dieless tube drawing conditions such as tensile speed and material properties on the deformation behavior of the tube. In the calculation, the material properties were dealt with as a function of temperature in a special subroutine, whose constitutive equation considering strain rate sensitivity and strain hardening was used, and was linked to the solver. FEM results for both heat transfer and the deformation profile are in good agreement with experimental results. Therefore, the validity of FE modeling of superplastic dieless drawing is demonstrated. In addition, the effect of material properties m and n values on the deformation profile is demonstrated numerically. As a result, a higher m value constrains the local instability deformation. In cases where the m value is high, the n value has little effect on the deformation profile. Consequently, it is found that analysis considering strain rate sensitivity is important for the prediction of the deformation profile in the dieless drawing process. [doi:10.2320/matertrans.P-MRA2008837]

(Received January 25, 2008; Accepted September 29, 2008; Published December 3, 2008)

Keywords: dieless tube drawing, finite element method, strain rate sensitivity, heat transfer

1. Introduction

Recently, the manufacture of ultrafine and high-precision processed components has led to the enhancement of the functions of medical and biological equipment, and equipment used for communication and measurement, and has contributed to developments in the fields related to micro-electro-mechanical systems (MEMS). In particular, ultrafine microtubes are expected to be applicable in various devices, such as mechanical/structural components in cooling micro-nozzles, electrode tubes used in electric discharge machining, contact probes, and painless needles.¹⁾

We proposed superplastic dieless drawing for fabricating microtubes and succeeded in fabricating a microtube with an outer diameter of $D = 343\ \mu\text{m}$ and an inner diameter of $d = 161\ \mu\text{m}$ without using fine dies, which otherwise cause various problems at micro-scale, while maintaining the ratio of the inner to outer diameters. Thus, the effectiveness of superplastic dieless drawing was demonstrated.^{2,3)} Moreover, the effects of the drawing conditions on the deformation profiles were examined.

Investigating the effects of various factors independently, such as processing conditions and material properties, by means of experiments is, however, limited. In addition, it is very difficult to experimentally observe in detail the deformation behavior of tubes during dieless drawing at micro-scale. Therefore, no detailed experimental study was presented in the previous report,^{2,3)} indicating the necessity of a numerical investigation.

In a numerical study on dieless drawing, Kobatake *et al.* calculated temperature distribution by the finite element method (FEM) considering heat transfer obtained by the deformation profiles during dieless drawing experimentally.⁴⁾ The temperature distribution in the axial direction obtained by the analysis showed good agreement with experimental results, indicating the effectiveness of the analysis. However,

only heat conduction was considered and deformation behavior was not included in the analysis; therefore, the effects of each factor on the deformation behavior were not investigated. Wang *et al.* calculated the dieless drawing force in a steady state on the basis of the energy principle and studied the effects of various factors on the drawing force.⁵⁾ However, the effect of heat transfer and the deformation behavior in an unsteady state were not considered, resulting in an insufficient analysis. Moreover, we previously carried out the FE simulation coupled with the thermo-mechanical analysis of dieless drawing, taking heat conduction inside a tube into consideration.⁶⁾ However, in the conventional model, the temperature distribution on the tube surface had to be determined beforehand by presetting the heating and cooling temperatures and the distance between the heater and the cooler. In fact, the temperature distribution on the tube surface was unknown because the temperature distribution should be determined by the amount of heat supplied from the heating coil and the heat transfer between the tube surface cooling air and atmosphere. Therefore, the conventional model was ineffective for studying the effects of the conditions, such as the amount of heat supplied from the heating coil and the efficiency of the cooling coil, on the temperature distribution.

In this study, we made a new heat transfer model in which we consider the amount of heat supplied from the heating coil and the heat transfer between the tube and the cooling coil and that between the tube and the atmosphere. A material with strain rate sensitivity and strain hardening dependence, as well as their temperature dependences, were considered was modeled as a tube. The FE simulation coupled with the thermo-mechanical analysis of superplastic dieless drawing, in which the evaluation of the heat transfer on a tube surface and the heat conduction inside the tube was coupled with the deformation analysis, was carried out. More concretely, we analyzed the dieless drawing of the Al-78Zn superplastic alloy, which was also used in the previous study, compared the results with the previous experimental results,^{2,3)} and demonstrated the effectiveness of the present analysis. The

*This Paper was Originally Published in Japanese in J. JSTP **48** (2007) 51–55.

Fig. 1 Schematic illustration of superplastic dieless drawing process.

effects of each factor on the drawing behavior were then investigated. In particular, for the effects of drawing conditions and material properties on the deformation profile, the aspects that cannot be elucidated in detail by experiments were numerically studied.

2. Superplastic Dieless Drawing

Superplastic dieless drawing is a method of fabricating a thin tube by the following procedure: fix one end of a superplastic alloy tubular material, as shown in Fig. 1, heat part of the material and then draw the other end of the material at speed V_1 . Simultaneously move the heated deformation region at speed V_2 . The cross-sectional areas of the tube before and after deformation are A_1 and A_2 , respectively. The reduction in area r is obtained as⁷⁾

$$r = 1 - A_2/A_1 = V_1/(V_1 + V_2). \quad (1)$$

It is possible to obtain a large r using a superplastic material with a high ductility for the original tube.

3. FE Analysis of Superplastic Dieless Drawing

3.1 FE model for superplastic dieless drawing

MSC.Marc/Mentat ver. 2001 was used as the commercial FEM code to analyze superplastic dieless drawing. The coupled thermo-mechanical rigid-plastic FE simulation was carried out. As shown in Fig. 2, an axisymmetric model was used in the FE model. The dimensions of the tube were used in the previous experiment:^{2,3)} outer diameter $D = 2$ mm and inner diameter $d = 1$ mm. The length of the tube was $l = 50$ mm. The number of elements was 500 in the axial direction and 4 in the tube thickness direction, and a 4-node axisymmetric element was used. The left end of the tube was fixed and tensile deformation was applied to the right end of the tube at tensile speed V_1 .

3.2 Heat transfer model

The temperature distribution of the tube during dieless drawing was changed in accordance with the heat supplied from the heating coil, the heat conduction inside the tube, and the heat transfer from the tube to the cooling air from the cooling coil and that from the tube to the atmosphere. The heat conduction equation of the axisymmetric model in an unsteady state considering the above factors is expressed as

$$\lambda \left\{ \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right\} - c\rho \frac{\partial T}{\partial t} + \dot{Q} = 0. \quad (2)$$

Here, λ is the thermal conductivity, c is the specific heat, ρ is

Fig. 2 FE model of superplastic dieless drawing process.

Fig. 3 Heat transfer model on tube surface in FE analysis of superplastic dieless drawing process.

the mass density, and $\dot{Q}$ is the heat generated per unit time and unit volume.

The tube is heated by the heat supplied from the heating coil and cooled by the cooling air from the cooling coil and the atmosphere. In this analysis, the boundary conditions for the heat transfer at the tube boundaries are as shown in Fig. 3. The heat is transferred through these boundaries, where the following boundary conditions are satisfied.

3.2.1 Heat transfer inside heating coil

Heat is transferred on the tube surface by the heating coil, and the following boundary condition is satisfied on the tube surface.

$$-\lambda \frac{\partial T}{\partial n} = q \quad (3)$$

The heat flux q outside the heating coil ($z < h_z$ and $h_z + h_w \leq z$) is defined as

$$q = 0 \quad (4)$$

and that inside the heating coil ($h_z \leq z < h_z + h_w$) is defined as

$$q = q_s. \quad (5)$$

Here, h_z is the position coordinate of the heating coil on the z axis, h_w is the width of the heating coil, and q_s is the amount of heat flux supplied.

Because the heating coil is moved at speed V_2 in time t , h_z is expressed as

$$h_z = h_{z0} - V_2 t. \quad (6)$$

Here, h_{z0} is the initial position coordinate of the heating coil on the z axis.

3.2.2 Heat transfer between tube and cooling coil and that between tube and atmosphere

Heat transfer occurs between the tube surface and the

cooling air from the cooling coil and between the tube surface and the atmosphere, and the following boundary condition is satisfied.

$$-\lambda \frac{\partial T}{\partial n} = h(T - T_c) \quad (7)$$

Here, h is the heat transfer coefficient and T_c is the atmospheric temperature. In the analysis, the air flowing from the inside to the outside of the cooling coil was modeled assuming that h gradually changes. Namely, h outside the cooling coil ($z < c_z - c_e$ and $c_z + c_w + c_e \leq z$) is defined as

$$h = h_a. \quad (8)$$

h in the region outside the cooling coil where the effect of cooling air is observed ($c_z - c_e \leq z < c_z$ and $c_z + c_w \leq z < c_z + c_w + c_e$) is defined as

$$h = \frac{(h_c - h_a)}{c_e} \{z - (c_z - c_e)\} + h_a \quad (9)$$

$$(c_z - c_e \leq z < c_z),$$

$$h = \frac{(h_c - h_a)}{c_e} \{(c_z + c_w) - z\} + h_c \quad (10)$$

$$(c_z + c_w \leq z < c_z + c_w + c_e),$$

and h under the cooling coil ($c_z \leq z < c_z + c_w$) is defined as

$$h = h_c. \quad (11)$$

Here, c_z is the position coordinate of the cooling coil on the z axis, c_e is the distance which is affected by the cooling air, c_w is the width of the cooling coil, h_a is the heat transfer coefficient between the tube surface and the atmosphere, and h_c is the heat transfer coefficient between the tube surface and the cooling air from the cooling coil.

Because the cooling coil is moved at speed V_2 in time t , similarly to the heating coil, c_z is expressed as

$$c_z = c_{z0} - V_2 t. \quad (12)$$

Here, c_{z0} is the initial position coordinate of the cooling coil on the z axis.

The thermal properties of the material are a specific heat c of $383 \text{ J kg}^{-1} \text{ K}^{-1}$, a mass density ρ of $7,130 \text{ kg m}^{-3}$, and a thermal conductivity λ of $113 \text{ W m}^{-1} \text{ K}^{-1}$. The heat transfer coefficient between the material and the atmosphere h_a is $30 \text{ W m}^{-2} \text{ K}^{-1}$, and the atmospheric temperature and the temperature of the cooling air are both 293 K .

In this analysis, the amount of heat (q_s) and the heat transfer coefficient (h_a, h_c) are assumed to be constant values. In the case of the analysis with higher precision, it is better to set the amount of heat and the heat transfer coefficient on the basis of the actual heating and cooling sources. For example, when modeling the high-frequency-induced heating, a more precise analysis can be realized by adding the coupled electromagnetic-thermal analysis and calculating the amount of heat generated to this model. In this case, however, it is necessary to prepare a numerical model in which all of electromagnetic-thermo-mechanical factors are coupled, which is very complicated. In this report, only the coupled thermo-mechanical analysis was taken into consideration for simplicity.

Fig. 4 Material properties of Al-78Zn alloy used in FEM analysis.

3.3 Material model

In dieless drawing, a tube is fabricated by locally increasing the temperature. In general, the flow stress of a material is greatly affected by the strain rate at a high temperature. Particularly in the case of the superplastic material used in this study, the strain rate sensitivity of the flow stress is very high. Now, we apply the following flow stress function considering the strain hardening dependence and the strain rate sensitivity into consideration to the material model dealt with in this analysis.

$$\sigma = K \dot{\epsilon}^n \epsilon^m \quad (13)$$

Here, K is the strength coefficient, n is the drawing hardening index, and m is the strain rate sensitivity index. Moreover, K , m , and n are assumed to approximately be functions of temperature.

Al-78Zn superplastic alloy, which was used in the experiment, was used as the material in this analysis. Because this material rarely hardens even at room temperature, $n = 0$ was assumed in every temperature range. The other material properties K and m were obtained by the jump tensile test in the temperature region between room temperature and 523 K in the range of strain rate between 4.17×10^{-4} and 10^{-2} s^{-1} , and were defined to be functions of temperature on the basis of the test result (Fig. 4).

3.4 User subroutine

The boundary condition of heat transfer and the material model defined in the previous section were incorporated into MSC.Marc employing user subroutines to carry out the FE simulation coupled with the thermo-mechanical analysis, considering the strain rate sensitivity, as shown in Fig. 5.

4. Analytical Results and Discussion

4.1 Validity of heat transfer analysis

To demonstrate the validity of the heat transfer model, the temperature distribution on the tube was experimentally measured by moving the heating and cooling coils at $V_2 = 3.6 \text{ mm/min}$ without applying tensile deformation. The apparatus and method of dieless drawing were the same

Fig. 5 Flow chart of coupled thermo-mechanical analysis and subroutine program.

Fig. 6 Effect of heat transfer coefficient under cooling coil on temperature history.

as those used in the previous study.^{2,3)} The experiments were carried out under condition of the high-frequency powers of 45 and 60% without cooling and with the cooling air pressure of 0.2 MPa.

Figure 6 shows the effect of the heat transfer coefficient under the cooling coil on the temperature distribution of the tube. FE analysis conditions were as follows: amount of heat supplied $q_s = 400 \text{ kW m}^{-2}$ and heat transfer coefficient under the cooling coil $h_c = 0\text{--}2,000 \text{ W m}^{-2} \text{ K}^{-1}$. With increasing h_c , the temperature decreases in general. Also in the experiment, the temperature in the case of applying 0.2 MPa cooling air generally decreases more than that in the case without cooling, indicating that the FE analysis well simulates the experiment. Figure 7 shows the effect of the amount of supplied heat on the temperature distribution of the tube. FE analysis conditions were as follows: $q_s = 400\text{--}1,500 \text{ kW m}^{-2}$ and $h_c = 2,000 \text{ W m}^{-2} \text{ K}^{-1}$. With increasing q_s , the temperature increases in general, which is in good agreement with the experimental results. By this comparison of the analysis and experimental results, the validity of the heat transfer model used in this analysis was verified.

Fig. 7 Effect of heat flux under heating coil on temperature history.

Fig. 8 Effect of tensile speed, V_1 on deformation profile in superplastic dieless drawing process (a) $V_1 = 3.6 \text{ mm/min}$, $V_2 = 3.6 \text{ mm/min}$, $r = 50\%$ (b) $V_1 = 7.2 \text{ mm/min}$, $V_2 = 3.6 \text{ mm/min}$, $r = 66.7\%$ (c) $V_1 = 10.8 \text{ mm/min}$, $V_2 = 3.6 \text{ mm/min}$, $r = 75\%$ (d) $V_1 = 14.4 \text{ mm/min}$, $V_2 = 3.6 \text{ mm/min}$, $r = 80\%$.

4.2 Effects of tensile speed on deformation profile

The deformation profile was observed after superplastic dieless drawing while maintaining the moving speed of the heating coil V_2 at 3.6 mm/min and changing the tensile speed V_1 in the range of 3.6–14.4 mm/min. The analysis was carried out by setting $q_s = 1,100 \text{ kW m}^{-2}$ such that the temperature of the heated part of the tube was approximately 523 K. Figure 8 shows the deformation profiles under conditions of the experiment and analysis. With increasing V_1 , the reduction in area r increases and the outer diameter of the tube D decreases. Moreover, unstable deformation in the initial stage of dieless drawing can be observed also in the FE analysis results. The degree of unstable deformation is defined as the unstable deformation rate $\Delta D/D_{\text{ave}}$.

Fig. 9 Relationship between ratio of instability deformation, $\Delta D/D_{ave}$ and reduction in area, r .

$$\frac{\Delta D}{D_{ave}} = \frac{D_{ave} - D_{min}}{D_{ave}} \quad (14)$$

Here, D_{ave} is the average outer diameter in the steady state and D_{min} is the minimum outer diameter of the unstably deformed part.

Figure 9 shows the relationship between $\Delta D/D_{ave}$ and r . $\Delta D/D_{ave}$ increases with increasing r . The higher the $\Delta D/D_{ave}$, the higher the risk of fracture in an unsteady state in the initial stage of drawing. In the experiment, drawing with r of more than 80% failed and fracture occurred. Here, we judged that $\Delta D/D_{ave}$ can be used as an index for evaluating the risk of fracture. The analysis result shows good agreement with the experimental result, indicating that the behavior during dieless drawing in the unsteady state until reaching the steady state is well simulated.

4.3 Effects of material characteristics on deformation profile

In the previous study,^{2,3)} the effect of the temperature of the heated part on the deformation profile was examined, and it was found that the unstable deformation can be suppressed at an appropriate temperature. We considered this to be due to the effect of n value being temperature dependent. However, some other parameters also depend on the temperature, and it is impossible to individually determine each effect of various material characteristics, including m value, experimentally. In the present analysis, we focused on the individual effect of m and n values on the deformation profile. Figure 10 shows the temperature dependences of m and n values. The relationship between the material characteristics and the temperature from room temperature to 523 K was approximated to be linear. The representative m and n values were the values at 523 K and room temperature, respectively. K value was set to be the same as that of the Al-78Zn alloy shown in Fig. 4. The analysis was carried out under the conditions of $V_1 = 3.6$ mm/min, $V_2 = 3.6$ mm/min, and $r = 50\%$.

Fig. 10 Temperature dependency of m and n values used in FEM analysis (a) m value (b) n value.

Fig. 11 Effect of m value on deformation profile in dieless drawing process (a) $m = 0.1$, $n = 0.2$ (b) $m = 0.2$, $n = 0.2$ (c) $m = 0.5$, $n = 0.2$.

Fig. 12 Effect of m and n values on instable deformation ratio $\Delta D/D_{ave}$ in dieless drawing process.

Figure 11 shows the effect of m value on the deformation profile. When m value is 0.1 or less, unstable deformation locally occurs, resulting in necking. The unstable deformation is suppressed with increasing m value.

Figure 12 shows the effects of m and n values on $\Delta D/D_{ave}$. As described above, the magnitude of m value greatly affects $\Delta D/D_{ave}$. Generally, $\Delta D/D_{ave}$ is suppressed with high m value regardless of n value, suggesting a low probability of

breakage in the unsteady state. On the other hand, n value affects $\Delta D/D_{\text{ave}}$ greatly in the case of low m value but negligibly in the case of high m .

These results reveal that m value under high-temperature conditions affects the deformation profile more greatly than n value at room temperature during dieless drawing. Here, the deformation behavior in the unsteady state is considered to be the same as that upon the occurrence of necking during tensile testing. Namely, in the case of a material with high m value, when the strain rate of the necking part increases, the flow stress increases and further deformation is suppressed. This behavior also occurs in the unsteady state during dieless drawing and the unstable deformation behavior is suppressed. Most materials exhibit strain rate sensitivity at high temperatures, which also illustrates the importance of taking into consideration the strain rate sensitivity index m value in the analysis. Moreover, to achieve successful drawing without unstable deformation, it is necessary to select a material with high m , such as superplastic materials, regardless of the magnitude of n value at room temperature. The analytical results reveal the effectiveness of superplastic dieless drawing proposed in this study. Furthermore, for a material with low m under high-temperature conditions, selecting a material with high n value at room temperature is effective for achieving successful drawing.

5. Conclusions

In this study, we developed an FE model with coupled analysis for superplastic dieless drawing, in which a material with strain rate sensitivity and strain hardening sensitivity, the heat transfer, and the deformation were taken into consideration. The validity of the model and the effects of

each condition on the deformation profile were studied, and the following conclusions were obtained.

- (1) The validity of the numerical model was demonstrated from the aspects of heat transfer and deformation. The results of FE analysis agreed well with the temperature distribution and the deformation profile obtained in the experiments, indicating the validity of the FE simulation coupled with thermo-mechanical analysis.
- (2) The effects of m and n , which are material characteristics with temperature dependence, on the deformation profile were investigated. As a result, it was found that m greatly affects the deformation profile, whereas n value affects the deformation profile only in the case of a material with low m value. The importance of taking into consideration the strain rate sensitivity during dieless drawing was verified.
- (3) It was found that the higher the m value of a material, the more the unstable deformation is suppressed. This demonstrates the effectiveness of superplastic dieless drawing numerically.

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