Development of Model Materials for Physical Forming Simulation of Metals and Alloys*

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In conjunction with experimental simulation of metal forming, the development of model materials, by which forming simulation can be carried out at a low stress level at room temperature, was performed. The model materials are mixtures of microcrystalline wax, rosin, mineral oil and powder. The flow curves of the model materials show three typical configurations, i.e., work-softening type, steady state deformation type and work-hardening type, which are observed in metals and alloys. The above configurations of the flow curves of the model materials could be changed and controlled by adjusting powder content. The flow curves of the model material could be predicted accurately using the work-hardening rate equation determined in this work. As an application example, experiments on and visio-plasticity analyses of the plane strain backward extrusion of magnesium alloy and its model material, which represent the deformation property of work-softening type materials, were carried out. We confirmed that the material flow and strain conditions in both materials correspond to each other with sufficient accuracy for engineering purpose.

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1. Introduction

The simulation of metal forming is widely recognized and utilized as the technology to support the design of the metal forming process which related to deformation properties of material, die and tool configuration, processing temperature, processing speed and processing conditions, complicatedly. As is well known, the methods for simulating a metal forming process can be divided into two categories: (1) experimental (physical) simulation, in which the forming phenomenon is elucidated by carrying out an experiment and by analyzing the experimental results (visioplasticity analysis). (2) computer (logical) simulation, in which the forming phenomenon is expressed using a mathematical model with several equations (finite element method), which is solved by calculating the change in the parameter that represents the forming conditions. Since in experimental simulation, the deformation process of the product and its plastic flow are measured, it is an effective method for understanding a deformation process clearly when the friction condition between the working material and the die and tool and the deformation properties of the material are not known. Further, when oil clay or wax is used as a substitute material (model material) for the actual metallic material in the simulation, forming experiments on forging, extrusion, and rolling processes can be easily simulated at a low stress level and at room temperature. Moreover, experimental simulations using the model materials are convenient for visualization analysis of plastic flow.1–5) Remark is that the model material used in the simulation of metal forming processes must have deformation properties similar to those of the actual metallic material.

It is well known that a flow curve (a true stress–true strain curve measured by uniaxial compression test) that represents the deformation properties of a metallic material quantitatively is affected by the temperature and strain rate in deformation process.6) The flow curve measured at constant temperature and at constant strain rate shows work-hardening type of deformation in the temperature range between room temperature and warm-working temperature and steady state type or work-softening type of deformation in the temperature range corresponding to hot-working temperatures.

In the present investigation, we developed a model material that can exhibit all the three above-mentioned types of deformation at room temperature. This material was the wax clay in which the appropriate amount of powder was added and refined in the wax. Further, the blending conditions for the model materials were determined, and an equation for predicting the flow curves of the model materials was proposed.

As an application example, experiments on and visioplasticity analyses of the plane strain backward extrusion of magnesium alloy and its model material, which represent the deformation property of work-softening type in the hot-working process, were carried out and we studied in similarity comparison of the equivalent strain distribution of the product inside.

2. Experimental Procedure

2.1 Experimental materials

The model material used in the experiment carried out in this study was prepared by using wax clay, which was mixed with powder and wax, and the obtained mixture was then kneaded. wax was composed of microwax, mineral oil and rosin, and the powder used is a mixture of kaolin and lime.
The compositions of all the model materials are shown in Table 1. The mass ratio of the components in the soft wax (Sample No. 1–9 in Table 1) was microwax : mineral oil : rosin = 5 : 1 : 1. While, hard wax (Sample No. 10–18 in Table 1) was composed of only microwax. Goodness of mixed state of the powder and wax and remarkable change of deformation properties were confirmed, then the model materials were prepared with different powder content in which powder component mass ratio is kaolin : lime = 2 : 5.

2.2 Preparation of model material and uniaxial compression test

A surfactant (Noigen ET-129 manufactured by Dai-Ichi Kogyo Seiyaku Co., Ltd.) and the powder were mixed with wax, which was melted in an oil bath heated to 150°C to obtain the compositions listed in Table 1. After cooling, the mixture of wax and powder were homogenized by kneading for 60 min using a two-axis kneading machine (PLASTI CORER-PL2000 manufactured by Brabender Co., Ltd.).

The model material obtained after kneading was heated at 150°C, and melted again in order to cast in a metal barrel mold of Φ40 × 150 mm. The mold was cooled and the model material solidified at around −20°C. A cylindrical specimen of Φ40 × 40 mm was prepared from the above model material by cutting the both ends with nylon thread to 40 mm height. Using the above specimen coated with Vaseline equally, the flow curves were measured by uniaxial compression till 50% of initial height (strain 0.7) using autograph in the condition of 25°C and compression speed 1 mm/s. Strain rate in a compression test at a constant ram speed was changed from 0.025 s⁻¹ to 0.05 s⁻¹ with an increase in the strain from 0 to 0.7. In order to investigate the influence of strain rate on the flow curve of the model materials, additional uniaxial compression tests were carried out at

the strain rate variation from 0.05 s⁻¹ to 0.1 s⁻¹ with a change in the strain from 0 to 0.7 by using Φ20 × 20 mm specimens. Then, the flow curves measured at the above two strain rate variations were compared each others.

In addition, it was confirmed that uniaxial compression tests of homogeneous deformation could be carried out by observation of outer profile of the specimens deformed in the above experiments.

2.3 The processing experiment of plane strain backward extrusion

The commercial magnesium alloy specimen used in this experiment was AZ31B plate with thickness of 6 mm (manufactured by Osaka Fuji Co., Ltd., and annealed specimen with hardness, HV = 65). After cutting out a 60 × 20 mm, the fine grid lines, spaced 2 mm apart, were scribed on the specimen. Two specimens were stacked together and used as a workpiece in the experiment. In the above workpiece preparation, one of the mating surfaces was the plane on which the grid lines were scribed and that plane became observation aspect of plastic flow (distorted grid line pattern).

Figure 1 shows the schematic sketch of the experimental apparatus of the plane strain backward extrusion. After the specimen spread with lubricant MoS₂ uniformly was placed into the die, backward extrusion (incremental forming test) was carried out at a material temperature of 300°C and ram speed of 0.5 mm/s using the hydraulic press machine and tubular electric resistance furnace.

The model material was a wax clay (No. 11 listed in Table 1) representing the similar deformation properties and flow curve configuration to those of the AZ31B specimen deformed at 300°C, and the model material specimen with the same dimensions as those of the AZ31B specimen was prepared. The grid lines spaced 2 mm apart were printed on one side of the model material specimen by the ink stamp. The two specimens of model material were stacked together, and placed into the plastic die as same as the previous description. The forming experiment was carried out under the same conditions as those in the uniaxial compression test; i.e., the temperature was maintained at 25°C, the punch ram speed was 1 mm/s and the specimen was lubricated using Vaseline. The plastic flow (distorted grid pattern) was then observed.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Wax/mass%</th>
<th>Powder/mass%</th>
<th>Powder content/mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66.6</td>
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<td>33.4</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>5</td>
<td>30.0</td>
<td>7.5</td>
<td>7.5</td>
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<td>6</td>
<td>26.6</td>
<td>6.7</td>
<td>6.7</td>
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<tr>
<td>7</td>
<td>23.4</td>
<td>5.8</td>
<td>5.8</td>
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<tr>
<td>8</td>
<td>25.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>9</td>
<td>13.4</td>
<td>3.3</td>
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<tr>
<td>18</td>
<td>20.0</td>
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</tbody>
</table>
3. Experimental Result and Discussion

3.1 Stress-strain curves of model materials

The stress-strain curves of the model materials prepared using the soft and hard wax are shown in Fig. 2. The configurations of the flow curves indicate that in the case of model materials prepared using soft wax with a powder content (Pw) of 0-55 mass% and those prepared using hard wax with Pw of 0-65 mass%, the work-softening type of deformation occurs and the maximum stress values are appeared at a strain of around 0.05. When powder content of the model materials was increased above the values mentioned above, steady state type and work-hardening type of deformation were observed. Further, the stress required to deform the model material prepared using hard wax is about seven or eight times higher than that required for model materials prepared using soft wax, and variance of stress deformation were observed. Further, the stress required to deform the model material prepared using hard wax is about seven or eight times higher than that required for model materials prepared using soft wax. Table 2 shows the values of experimental factors, C and n, in eq. (1) by which the flow curves (σ-ε curves) of materials in a strain range of more than 0.05 were represented. Where, eq. (1) is well known as the empirical rule equation for metallic materials. Then, the value of n could be controlled by varying powder content in wax.

\[ \sigma = C \varepsilon^n \]  \hspace{1cm} (1)

Figure 3 shows the flow curves at two different strain rates which were measured by uniaxial compression tests carried out at constant ram speed and using the specimens with different initial heights. Figures 3(A) and (B) show the strain rate variations with regard to strain. While, Fig. 3(A)' and (B)' represent the flow curves measured at the above strain rate variations. The flow curves corresponding to the strain rates \( \varepsilon_1 \) and \( \varepsilon_2 \) were compared in the case of both hard wax and soft wax, and we could confirm that strain rate dependence of flow stress of the model materials was the same as that of the metallic materials; i.e., deformation resistance is increased with increasing strain rate. Although the effect of strain rate on deformation resistance is low in the case of model materials with powder content of up to 60 mass%, it becomes remarkable that the strain rate does affect the deformation resistance of model materials with Pw of 80 mass%.

In the model material made of soft wax with Pw of 80 mass%, the flow curve measured at low strain rate (\( \varepsilon_2 \)) exists at higher stress level compared to that measured at high strain rate (\( \varepsilon_1 \)) up to strain 0.27. This is because the work-hardening rate in the early stage (strain 0 to 0.02) of deformation in the case of \( \varepsilon_1 \) is lower than that in the case of \( \varepsilon_2 \). Deformation characteristic at larger strain range than 0.02 represents that work-hardening rate becomes larger at higher strain rate which is the same characteristic as that observed.

![Fig. 2 Flow curves of the model materials using soft wax, (A), and using hard wax, (B).](image)

![Fig. 3 Effect of strain rate variation on the configuration of the flow curves; i.e., work-hardening type, steady state deformation type and work-softening type, using soft wax, (A)-(A)', and using hard wax, (B)-(B)'.](image)

Table 2  C and n value in eq. (1) of model materials show in Fig. 2.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder content/mass%</td>
<td>0</td>
<td>15</td>
<td>30</td>
<td>50</td>
<td>55</td>
<td>60</td>
</tr>
<tr>
<td>C value</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>n value</td>
<td>-0.43</td>
<td>-0.27</td>
<td>-0.21</td>
<td>-0.08</td>
<td>-0.03</td>
<td>0.01</td>
</tr>
</tbody>
</table>

![Table 2](image)
in the metallic materials. While, the abovementioned effects are not observed in the case of hard wax. The deformation characteristic of model materials using hard wax shows that work-hardening rate and deformation resistance increase with increasing strain rate as same as metallic materials in all strain region of deformation.

3.2 Equation for prediction of deformation resistance of model material

Up to the present, a number of research papers concerning the equation of deformation resistance in plastic deformation of metallic materials have been reported. An equation for predicting the deformation resistance of model materials was formulated on the basis of the experimental data shown in Fig. 2. The equation for predicting the deformation resistance was expressed using the work-hardening rate at a strain \( (\sigma/\varepsilon)_R \), in order to take into account the effect of the powder particles dispersed in wax on the deformation resistance \( \sigma \) at each moment (at a strain \( \varepsilon \)) during the deformation process. Equation (2) expresses the work-hardening rate at a strain \( (\sigma/\varepsilon)_R \), for the model materials, which is prepared by adding a certain amount of powder, as the sum of the work-hardening rate \( (\sigma/\varepsilon)_R \) (basic work-hardening rate) for 100% pure wax and the increase in the work-hardening rate \( (\sigma/\varepsilon)_R \) resulting from the addition of the powder.

The term representing the increase in the work-hardening rate \( ((\sigma/\varepsilon)_R \) in eq. (2)) at a strain \( \varepsilon \) was determined using the flow curves of 100% pure soft wax (Pw: 0 mass%) and of model materials with different powder contents (Pw: 30~50 mass%, shown in Fig. 2). Figure 4(A) shows the relationships between the increment of work-hardening rate \( (\sigma/\varepsilon)_R \) in each powder content of model material and strain \( \varepsilon \). In addition, the result that plotted relations between the mentioned above of \( (\sigma/\varepsilon)_R \) and \( \varepsilon \) to a semilogarithmic graph is shown in Fig. 4(B). In the case of \( \varepsilon > 0.1 \), that a reading error of flow curve in calculation of the value of term \( (\sigma/\varepsilon)_R \) and an error of finite difference calculation are small in Fig. 4(B), the relation of \( (\sigma/\varepsilon)_R \) plotted for each powder content and \( \varepsilon \) can be expressed approximately by the equation of a linear function (3) or the eq. (4) renewed in same one. In the equations, \( q \) and \( S_0 \) (or \( K \)) are experimental factors. The factor \( q \) did not depend on powder content and was found to have a value of 6.0. While, it was proved that \( S_0 \) (or \( K \)) was a material factor whose value changed with the powder content. In the case of a powder content for which \( (\sigma/\varepsilon)_R \) was extremely small (Pw: 30~55 mass%, shown in Fig. 4(B)), though the differences between an approximation straight line by the eq. (3) and the plotted points seems remarkable because of semi logarithm expression of a small numerical value, it was confirmed that an approximation with the eq. (3) could be approved by an confirmation calculation to mention later.

\[
\left[ \frac{\partial \sigma}{\partial \varepsilon} \right] = \left[ \frac{\partial \sigma_0}{\partial \varepsilon} \right] + \frac{\partial \sigma}{\partial \varepsilon} \quad (2)
\]

\[
\ln \left[ \frac{\partial \sigma}{\partial \varepsilon} \right] = -q \cdot \varepsilon + S_0 \quad (3)
\]

\[
\left[ \frac{\partial \sigma}{\partial \varepsilon} \right] = K \exp(-q \cdot \varepsilon), \quad K = \exp(S_0) \quad (4)
\]

Similarly, the analysis results for the model materials prepared using hard wax showed that the value of \( q \) was 6.0 and that the value of \( K \) changed with powder content. Since the same powders were added in soft and hard wax, the hardening mechanism is thought about with a similar result. The relationships between powder content and \( K \) in the case of materials prepared using soft and hard wax are shown in Fig. 5.

From the results of the abovementioned experiment and the analytical procedure, the equation of flow curve prediction for model materials could be expressed by eq. (5).

\[
\left[ \frac{\partial \sigma}{\partial \varepsilon} \right] = \left[ \frac{\partial \sigma_0}{\partial \varepsilon} \right] + K \exp(-q \cdot \varepsilon) \quad (5)
\]

Being alliance the segmental second order polynomial equations which represented relations of \( K \) and powder content of Fig. 5 and eq. (5) that \( q = 6.0 \) was substituted for, a computer program to do numerical calculation by Runge–Kutta-Gill method was cored. Then, the flow curves of model materials containing some different powder content
were calculated by using the program. Figure 6 shows comparisons between the calculated (plotted solid circles and broad lines) and experimental results (plotted open circles and fine lines solid lines) for material prepared using soft wax. We can confirm that the results of flow curves predicted by using the equation of work-hardening rate are in good agreement with the actual measurement results.

3.3 Experiment on plane strain backward extrusion

The experiment and the visioplasticity analyses on the plane strain backward extrusion of magnesium alloy (AZ31B) and of the model material corresponding to AZ31B were carried out, and the equivalent strain distributions in the products were compared mutually. It was known that plastic deformation of magnesium alloy is difficult at room temperature, but it is possible at a temperature of more than 200°C. Therefore, the extrusion experiment using magnesium alloy was carried out at 300°C.

The solid line in Fig. 7 shows the flow curve of magnesium alloy (AZ31B) measured at 300°C and at a punch ram speed of 0.5 mm/s. The flow curve of the alloy indicates the work-softening phenomenon due to dynamic recrystallization occurring during a deformation process. We chose the model material No. 11 listed in Table 1 (hard wax, Pw = 15 mass%) softening type of deformation observed in deformation of AZ31B. The dotted line in Fig. 7 shows the flow curve of the model material made of hard wax and powder (Pw = 15 mass%), which was shown in Fig. 2(B).

When the flow curve of model material is compared with that of AZ31B, the stress level of deformation resistance is lower about 1/200. Further, in the strain range exceeding 0.15, it can be confirmed that the work-softening type of deformation indicated by both the flow curves are similar.

A series of incremental forming experiments in which the punch stroke stopping positions were changed some amount from a forming start position was carried out in order to analyze the plane strain backward extrusion process (non-steady state deformation) by applying the visioplasticity method.\(^5\) Change of the grid pattern, which had been scribed on (magnesium alloy) or printed on (model material) the observation plane of material flow of the workpiece, with regard to forming time was used for the numerical analysis. The equivalent strain distributions in the products at about 6 mm punch stroke position are shown in Fig. 8. It can be confirmed that the equivalent strain distribution in the product of the model material and that in the product of AZ31B are the similar result.
4. Conclusions

A series of experiments and analyses were carried out for development of the model materials corresponding to the metallic materials by which a physical simulation of metal forming can be performed at a low stress level and at room temperature.

Deformation properties similar to those of metallic materials could be represented by the model materials made of wax clay in which the appropriate amount of powder was added and refined in the wax. The deformation characteristics (configuration of flow curves) could be corresponded to three typical configurations (work-softening type, steady state type and work-hardening type of deformation) by adjusting the powder content. In addition, we proposed the work-hardening rate equation by which the flow curves of the model materials with different powder contents (Pw) could be predicted accurately, and the model material representing an arbitrary flow curve configuration could be fabricated.

As an application example, the experiments and strain analyses by visioplasticity method on the plane strain backward extrusion of AZ31B and its model material representing work softening type of deformation were carried out. We confirmed that product configuration, material flow in a forming process and strain distribution in the product of the actual material could be predicted with sufficient accuracy for engineering purposes by carrying out a physical forming simulation using the model material developed in the present investigation.

REFERENCES