Finite element analysis of shape accuracy of billet
cold-forged with stepwise ram motion

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Abstract
Influence of stepwise ram motion, one of practical ram motion controls of servo press, on shape and dimensional accuracies of forged billet was investigated in cold cup forging process by the finite element analysis. In the process with stepwise ram motion, the billet inserted in the container was forged by the punch with upper ram of press, and the punch was operated with repetition of advance and pause modes. Following four stages were analyzed; (i) forging, (ii) removal of the punch from the forged billet, (iii) ejection of the forged billet from the container by the knockout punch and (iv) air cooling of the forged billet. In the analysis, the shape and dimensional changes of the inner wall of the billet during the four stages were investigated with several stepwise ram motions under the same forging duration. It is found that repetition of the punch advance with short stroke reduces heterogeneity of the temperature and stress distributions, so that the shape and dimensional accuracies of the inner wall of the forged billet were improved. The results of the finite element analysis were confirmed to be qualitatively agreed with the results of forging experiment on a link-type servo press.

Keywords: Forging, Process, Stepwise ram motion, Servo press, Shape accuracy, Dimensional accuracy, Finite element analysis

1. Introduction

Shape and dimensional accuracies of forged or extruded billet are mainly determined by temperature, stress and strain distributions in the billet during forging or extrusion process (Long and Balendra, 1998, Ishikawa et al., 2000). The distributions are complexly affected by heat generation by plastic deformation of billet, friction and heat transfer at die–billet interface, and rigidity of die and press machine (Kudo, 1988, Altan et al., 2005). The control of the distributions is traditionally carried out by adjusting the forming speed, the die shape and dimension (Matsubara, 1976, Imai, 1981), however, the control range of the distributions is considerably limited. In addition, the control is strongly depended on the basis of experience of forging operation. For these reasons, the relationship between the distribution and the accuracies is not clearly discussed.

Owing to the development and spread in the use of servo presses in metal forming industries (Osakada et al., 2011), control of the ram speed and motion is an attractive means for controlling the above phenomena. In cold forging with pulsed ram motion, of which the ram is operated with a manner that combined pulsed (repetition of advance and retreat) and stepwise modes, the shape accuracies of forged hole and extruded wall of the billet were reported to be improved by controlling temperature distribution in the billet (Matsumoto et al., 2013, Ishikawa et al., 2014). In cold impact extrusion with decreasing ram speed motion, the shape accuracy of extruded wall was also reported to be improved by controlling temperature distribution in the billet (Shinomiya and Shirakawa, 2013). In sheet metal forming, springback of sheet was reported to be reduced by controlling elastic recovery of the formed sheet in bottoming ram motion (Mori et al., 2007) and attach-detach (pulsed) ram motion (Majidi et al., 2016).

Stepwise ram motion, one of practical ram motion controls of servo press for cold forging, is selected for investigation of shape and dimensional accuracies of forged billet in cold cup forging process in this study. Since the
ram is operated with repetition of advance and pause modes in the stepwise ram motion, the billet is not detached from the die during forging. The stepwise ram motion was reported to improve uniform elongation of steel sheet in tensile test owing to the stress relaxation with a relaxation duration of 60 s (Hariharan et al., 2013). The stepwise ram motion was also reported to improve forming limit of steel sheet in deep drawing test owing to the stress relaxation (Yamashita and Ueno, 2013).

In this study, the relationship between the stepwise ram motion (advance stroke, total step number and pause duration) and the shape and dimensional accuracies of the forged billet is investigated in cold cup forging process by the finite element analysis. The finite element analysis is employed because the above distributions in the billet during forging process are difficult to measure in forging experiments. The influence of the heat generation of the billet, the elastic deformation of the dies and the heat transfer at the die–billet interface on the accuracies is discussed. Furthermore, to confirm the validity of the results of the finite element analysis, forging experiment is demonstrated on a link-type servo press.

2. Ram motion and forging conditions

2.1 Stepwise ram motion

Figure 1 shows a schematic ram position–time diagram of stepwise ram motion. The upper ram was operated with repetition of advance and pause modes. The billet constantly contacted with the die during stepwise ram motion. The billet was deformed during the ram (punch) advance, while the temperature distribution in the billet was accommodated during the ram (punch) pause. To describe the ram motion, $s_{fi}$, $t_{fi}$, $t_{pi}$ and $n_{total}$ were defined as forging (advance) stroke in the $i$-th step, forging (advance) duration in the $i$-th step, pause duration in the $i$-th step and total step number, respectively. The total forging stroke ($s_{total}$), total forging duration ($t_{total}$) and average forging speed ($v_{avg}$) were defined as follows:

$$s_{total} = \sum_{i=1}^{n_{total}} s_{fi}$$  \hspace{1cm} (1)

$$t_{total} = \sum_{i=1}^{n_{total}} (t_{fi} + t_{pi})$$ \hspace{1cm} (2)

$$v_{avg} = s_{total} / t_{total}$$ \hspace{1cm} (3)

In this study, $s_{fi}$, $t_{fi}$ and $t_{pi}$ were set as constant. Thus, $s_{fi}$, $t_{fi}$ and $t_{pi}$ can be written as $s_{i}$, $t_{i}$ and $t_{pi}$, respectively.

![Fig. 1 Upper ram position–time diagram of stepwise ram motion (sf: forging stroke in the $i$-th step, tf: forging duration in the $i$-th step, tp: pause duration in the $i$-th step, stotal: total forging stroke, ttotal: total forging duration, ntotal: total step number, $i = 1$ to ntotal). The upper ram is operated with repetition of advance and pause modes. Billet is deformed during the ram advance.](image)

2.2 Forging conditions

Figure 2 shows the die arrangement of cup forging. The forging shape was symmetry with respect to x-axis and plane strain with respect to y-axis. A rectangular billet with 23.9 mm in width x 10 mm in thickness x 17 mm in height
inserted in a container was forged with a reduction in cross-sectional area of 0.33 by a punch with the upper ram. Here the billet was JIS: A6063-T5 aluminum alloy, while the dies (punch, knockout punch and container) were JIS: SKH55 high-speed tool steel. The initial temperatures of the billet and the dies were room temperature (293 K). The ram speed–position diagram was assumed that of a link-type servo press (Komatsu Industrial Corp., H1F45). The stepwise ram motions were set under conditions of $s_{\text{total}} = 12$ mm and $t_{\text{total}} = 0.86$ s ($v_{\text{avg}} = 14$ mm/s). The $s_f$, $t_p$ and $n_{\text{total}}$ were set in the range of 0–12 mm ($s_f/s_{\text{total}} = 0–1$), 0–0.6 s ($t_p/t_{\text{total}} = 0–0.72$) and 1–10, respectively. The designed (ideal) inner width and inner wall height of the forged billet with $s_{\text{total}} = 12$ mm were $w_{\text{des}} = 16$ mm and 36 mm, respectively, as shown in Fig. 2(c).

Fig. 2 Die arrangement and shapes of punch and forged billet for cup forging. The rectangular billet inserted in the container is forged by the punch with the upper ram. The land portion of the punch is 16 mm in width and approximately 2 mm in length. Thus the designed inner width of the forged billet is $w_{\text{des}} = 16$ mm.

3. Finite element analysis conditions

Finite element analysis was carried out by employing Simufact Forming ver. 11.0.2 (Simufact Engineering GmbH). In the analysis, elastic-plastic deformation and temperature change of the billet, punch and container were calculated, while the knockout punch and container ring were treated as rigid bodies with temperature change. The energy of the plastic deformation work in the billet and at the die–billet interface was calculated in the elastic-plastic finite element analysis. 90% of the energy of the plastic deformation work was treated as the heat flux in the heat conduction finite element analysis. Figure 3 shows the two-dimensional plane strain model of cup forging for finite element analysis. In symmetry of the die arrangement, the right-half part with a thickness in y direction of 10 mm was analyzed. The initial elements of the billet and dies were automatically created with 4-node quadrilateral elements with size of approximately 0.1 mm x 0.1 mm in the inside and approximately 0.05 mm x 0.05 mm at the surface. The element was automatically remeshed when the strain increment of the element exceeded 0.4 at a calculation step. Following four stages shown as Fig. 4 were analyzed with plane strain state with respect to y-axis; (i) forging, (ii) removal of the punch from the forged billet, (iii) ejection of the forged billet from the container by the knockout punch and (iv) air cooling of the forged billet. The material properties of the billet and dies were employed from the built-in database of material properties in Simufact Forming ver. 11.0.2. The model of the flow stress with isotropic hardening of A6063-T5 aluminum alloy was as follows:

$$\sigma = a_1 \exp(a_2 T) \varepsilon (n_1 + n_2) \exp\left(\frac{m_1 T + m_2}{\varepsilon}\right) \dot{\varepsilon} (m_1 T + m_2)$$  \hspace{2cm} (4)

where $\sigma$ (MPa) is flow stress, $\varepsilon$ is strain, $\dot{\varepsilon}$ ($s^{-1}$) is strain rate, $T$ (°C) is temperature, $a_1 = 1.96 \times 10^2$, $a_2 = -3.29 \times 10^{-2}$, $n_1 =$
-1.07 \times 10^{-3}, n_2 = 3.72 \times 10^{-4}, n_3 = -1.19 \times 10^{-4}, n_4 = 2.71 \times 10^{-2}, m_1 = 2.77 \times 10^{-4} and m_2 = -6.43 \times 10^{-3}. The material properties of A6063-T5 aluminum alloy and SKH55 high-speed tool steel are shown in Fig. 5. The temperature dependences of the flow stress, the Young's modulus, the thermal conductivity, the specific heat and the thermal expansion were accounted in the analysis, and the strain rate sensitivity of the flow stress was also taken into account. The Poisson's ratio of A6063-T5 aluminum alloy and SKH55 high-speed tool steel were 0.250 and 0.283, respectively. Crack initiation and microstructural change in the workpiece and the dies were not considered in the analysis. The shear friction factors at the die–billet interface and the container–ring interface were assumed to be 0.2 and 1.0, respectively. The heat transfer coefficients for the die–workpiece interface, the container–ring interface and the free surface of the billet were assumed to be \( h_{d-b} = 5000 \text{ W/(m}^2\text{K)} \), 5000 W/(m\(^2\)K) and 50 W/(m\(^2\)K), respectively.

Fig. 3 Two-dimensional plane strain model of cup forging for finite element analysis (thickness in y direction: 10 mm). In symmetry of the die arrangement, the right-half part is analyzed. The bottoms of the container and ring are fixed. The bottom of the knockout punch is fixed in forging stage.

Fig. 4 Four stages in cold cup forging process. Elastic-plastic deformation and temperature change of the billet, punch and container are analyzed with plane strain state with respect to y-axis in the four stages.
4. Finite element analysis results

4.1 Shape change of billet during cup forging process

Since the punch width of the upper part of the land portion (16 mm in width and approximately 2 mm in length) was 15.9 mm (see Fig. 2(b)) in cup forging process, once the inner wall of the billet was extruded by the land portion of the punch, the large part of the inner wall was deformable (free surface) without constraint of the punch. For this reason, the shape and dimension of the inner wall of the billet were measured. Figure 6 shows the x-z cross-sectional shape of the inner wall of the billet after each stage (i)–(iv). The inner wall was formed smaller than the designed dimension \((w_{des} = 16 \text{ mm})\) and it was slightly tilted toward the center direction \((x = 0 \text{ mm})\) at the stage (i). In case of forging with the stepwise ram motion \((s/s_{total} = 0.167 \times n_{total} = 6)\), the shape of the inner wall was waved in \(x\) direction corresponding to total step number \((n_{total})\) at the stage (i). The upper part of the inner wall was expanded to the outer direction by the punch removal at the stage (ii), so that the inner wall was straightened and standed. Due to elastic recovery by releasing from the container at the stage (iii), the bottom part of the inner wall was expanded to the outer direction, while the top part of the inner wall was shrunk to inner direction. As the result, the inner wall was tilted toward the center direction again. The inner wall was shrunk to the center direction \((x \text{ direction})\) due to heat shrinkage at the stage (iv). Thus the shape and dimension of the forged billet were determined via the deformations at the stages (i)–(iv).

![Fig. 6 x-z cross-sectional shape of inner wall of billet after each stage (i)–(iv) in cup forging process. The shape and dimension of the inner wall are changed at each stage (i)–(iv) due to elastic recovery and heat shrinkage of the billet.](image)

4.2 Shape and dimensional accuracies of forged billet

The shape and dimension of the inner wall of the forged billet after stage (iv) were investigated with \(n_{total} = 1–10\)
under \( v_{\text{avg}} = 14 \text{ mm/s} \). The average inner width \( (w_{\text{avg}}) \), coefficients of variation of the shape \( (C_{\text{shp}}) \) and dimension \( (C_{\text{dim}}) \) of the inner width were calculated as follows:

\[
 w_{\text{avg}} = \frac{\sum_{i=1}^{n} w_i}{n} \tag{5}
\]

\[
 C_{\text{shp}} = \frac{1}{\sqrt{n}} \frac{\sum_{i=1}^{n} (w_i - w_{\text{avg}})^2}{w_{\text{avg}}} = \frac{\sum_{i=1}^{n} (w_i^2 - w_{\text{avg}}^2)}{w_{\text{avg}}} \tag{6}
\]

\[
 C_{\text{dim}} = \frac{1}{n} \frac{\sum_{i=1}^{n} (w_i - w_{\text{des}})^2}{w_{\text{des}}} \tag{7}
\]

where \( w_i \) is the inner width and is measured every 1.0 mm interval in z direction. Figure 7 shows the coefficients of variation of the shape and dimension of the inner width. Both coefficients of variation with \( n_{\text{total}} \leq 4 \) \( (s/s_{\text{total}} \geq 0.25) \) were higher than those with \( n_{\text{total}} = 1 \) (no stepwise ram motion), while both coefficients of variation with \( n_{\text{total}} \geq 6 \) \( (s/s_{\text{total}} \leq 0.167) \) were lower than those with \( n_{\text{total}} = 1 \). This means that the repetition of the punch advance with short stroke is effective to improve the shape and dimensional accuracies of the inner wall. If the inner wall is formed with uniform width \( (C_{\text{shp}} = 0) \), it is relatively easy to form the inner width with the designed dimension \( (C_{\text{dim}} = 0) \) by adjusting the width dimension of the punch. Therefore, the shape accuracy \( (C_{\text{shp}}) \) is mainly investigated in following sections.

![Fig. 7 Coefficients of variation of shape and dimension of inner wall of forged billet after stage (iv) in cup forging process. Low coefficients of variation of shape and dimension mean high accuracies of shape and dimension, respectively.](image)

### 4.3 Temperature and stress distributions of forged billet

Figure 8 shows the temperature distributions in x-z cross-section of the billet during punch pause of stage (i) at \( s/s_{\text{total}} = 0.5 \). In the stepwise ram motions, heterogeneity of the temperature distribution was reduced during the punch pause (Fig. 8(b) and (c)) because the heat generated in the billet by plastic deformation of the billet before the punch pause was diffused from the larger-deformed part of the billet to the smaller-deformed part during the punch pause, and was transferred from the billet to the dies. As the result, next forming step started at the relaxed state of heterogeneity temperature distribution. The equivalent stress distributions in x-z cross-section of the billet during the punch pause of stage (i) at \( s/s_{\text{total}} = 0.5 \) are shown in Fig. 9. The stress distribution between the punch and knockout punch was hardly changed during the punch pause, while the stress distribution of the side wall was slightly relaxed (Fig. 9(b) and (c)). Since the stress relaxation occurred with maximum 20 MPa in less than 5% of the billet volume during the punch pause duration of maximum 0.36 s (Fig. 9(b)), the shape change of the side wall is considered to be hardly caused by the stress relaxation.

Figure 10 shows the temperature and equivalent stress distributions in x-z cross-section of the billet at \( s/s_{\text{total}} = 1 \) of stage (i). Heterogeneity of the temperature and stress distributions increased in the billet of \( s/s_{\text{total}} = 0.5 \times n_{\text{total}} = 2 \), while heterogeneity of the temperature and stress distributions decreased in the billet of \( s/s_{\text{total}} = 0.167 \times n_{\text{total}} = 6 \). Furthermore, it is indicated that the waved shape of the inner wall shown in Fig. 6 is induced by the spotted stress distribution at the center part of the side wall.
Fig. 8 Temperature distribution in x-z cross-section of billet during punch pause of stage (i) \( (s/s_{\text{total}} = 0.5) \). In the stepwise ram motions, heterogeneity of the temperature distribution is reduced during the punch pause. As the result, the billet starts to be deformed with the relaxed state of the heterogeneity temperature distribution at next forming step.

Fig. 9 Equivalent stress distribution in x-z cross-section of billet during punch pause of stage (i) \( (s/s_{\text{total}} = 0.5) \). In the stepwise ram motions, the stress relaxation slightly occurs in the side wall part during the punch pause.

Fig. 10 Temperature and equivalent stress distributions in x-z cross-section of billet at stage (i) \( (s/s_{\text{total}} = 1) \). Non-uniformity of the temperature and stress distributions decreased with decreasing forming stroke in the step \( (s) \) and increasing total step number \( (n_{\text{total}}) \).
From above results, it is found that the reductions of the heterogeneity of the temperature and stress distributions correspond with decreases of the coefficients of variation of the shape and dimension. Since the elastic recovery at the stage (iii) and the heat shrinkage at the stage (iv) are strongly affected by the temperature and stress distributions at the stage (i), it is concluded that the reductions of the heterogeneity of the temperature and stress distributions are effective to improve the shape accuracy of the forged billet. However, it is noticed that the production of the forged billet with completely uniform inner width is difficult to be realized by the ram motion control because the heterogeneity of the distributions must occur in non-uniform plastic deformation.

5. Discussions

5.1 Influence of pause duration

Figure 11 shows the coefficient of variation of the inner width shape of the forged billet after stage (iv) with $s_f/s_{total} = 0.167 \times n_{total} = 6$, $v_{avg} = 4.4–52$ mm/s and $t_{total} = 0.23–2.7$ s. The maximum pause duration in each step and the maximum total forging duration were set $t_p = 0.5$ s and $t_{total} = 2.7$ s, respectively. The coefficient of variation decreased with increasing pause duration because the heterogeneity of the temperature distribution was reduced during the punch pause, especially long pause duration was effective. Thus the punch pause with long duration is effective to improve the shape accuracy of the inner wall, however, the total forging duration becomes long, and the productivity of the forged billet becomes low.

![Fig. 11 Influence of pause duration in each step on coefficient of variation of shape of inner wall of forged billet after stage (iv) ($s_f/s_{total} = 0.167 \times n_{total} = 6$, $v_{avg} = 4.4–52$ mm/s and $t_{total} = 0.23–2.7$ s).](image)

5.2 Influence of temperature change of billet and elastic deformation of dies

The temperature and stress distributions of the billet are strongly affected by the heat generation by plastic deformation of the billet and the elastic deformation of the dies. To discuss the influence of the heat generation and the elastic deformation on the shape accuracy of the forged billet, the shape accuracy was compared with four analysis cases of (A)–(D) shown in Table 1. Here the temperature change was not calculated under the isothermal condition, and was kept to be at room temperature (293 K) (cases of (C) and (D)). In comparison between the case (A) and (C) or the case (B) and (D), the influence of the heat generation on the shape accuracy was investigated. In comparison between the case (A) and (B) or the case (C) and (D), the influence of the die rigidity on the shape accuracy was investigated.

Figure 12 shows the coefficient of variation of the inner width shape of the forged billet after stage (iv) in the analysis cases (A)–(D). The inner width with highest shape accuracy was obtained with isothermal and elastic die conditions. In addition, the shape accuracy in the analysis cases (A) and (B) was affected by the total step number, while the shape accuracy in the analysis cases (C) and (D) was almost constant with total step number. This indicates the influence of the temperature change of the billet during cold forging process on the shape change of the billet is large, while the influence of the die rigidity on the shape change of the billet is small. The equivalent stress distribution in x-z cross-section of the billet at $s/s_{total} = 1$ of stage (i) with $s/s_{total} = 0.167 \times n_{total} = 6$ in the cases (A)–(D) is shown in
Fig. 13. The spotted stress distribution at the center part of the side wall was seen in the cases (A) and (B), while the spotted stress distribution was not seen in the cases (C) and (D). It is indicated the spotted stress distribution was induced due to the temperature change in the billet by the plastic deformation, so that the waved shape of the inner wall shown in Fig. 6 is induced.

Table 1 Calculation cases in finite element analysis of cup forging process.

<table>
<thead>
<tr>
<th>Case</th>
<th>Billet, punch, container, knockout punch</th>
<th>Punch and container</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Non-isothermal</td>
<td>Elastic (deformable)</td>
</tr>
<tr>
<td>B</td>
<td>Non-isothermal</td>
<td>Rigid</td>
</tr>
<tr>
<td>C</td>
<td>Isothermal (no temperature change, 293 K)</td>
<td>Elastic (deformable)</td>
</tr>
<tr>
<td>D</td>
<td>Isothermal (no temperature change, 293 K)</td>
<td>Rigid</td>
</tr>
</tbody>
</table>

Fig. 12 Coefficient of variation of shape of inner wall of forged billet after stage (iv) in analysis cases (A)–(D). The coefficient in the cases (C) and (D) are almost constant with total step number. This indicates influence of die rigidity on the shape accuracy of the billet is small, while the influence of temperature change of the billet during cold forging process is large.

Fig. 13 Equivalent stress distributions in x-z cross-section of billet at stage (i) in analysis cases (A)–(D) ($\sigma$/stotal = 0.167 x ntotal = 6, s/stotal = 1).

5.3 Influence of heat transfer at die-billet interface

Since the temperature distribution of the billet is also affected by the heat transfer at the die–billet interface, the shape accuracy of the forged billet was calculated under four heat transfer conditions of $h_{db} = 1000$–300000 W/(m²·K). Here, die material with low thermal conductivity such as ceramic was supposed to be used in the case of $h_{db} = 1000$.
W/(m²·K), while die material with high thermal conductivity such as cemented tungsten carbide was supposed to be used in the case of \( h_{d,b} \geq 10000 \text{ W/(m}^2\text{·K)} \). Figure 14 shows the coefficient of variation of the inner width shape of the forged billet after stage (iv). Regardless of the heat transfer coefficient, the coefficient of variation decreased with increasing total step number. The coefficient of variation increased with increasing heat transfer coefficient, however, the increase of the coefficient of variation was small at \( h_{d,b} \geq 10000 \text{ W/(m}^2\text{·K)} \). The temperature and equivalent stress distributions in x-z cross-section of the billet at stage (i) are shown in Fig. 15. When the heat transfer coefficient was low, the temperature of the side wall of the billet was high, and the temperature difference between the outer and inner widths of the billet was small. This is because the heat generated by the plastic deformation of the billet is kept in the billet by blocking the heat transfer from the billet to the container. The stress distribution was slightly uniformed at low heat transfer coefficient. The spotted stress distribution was appeared at the center part of the side wall in all analysis with these heat transfer coefficients. The heterogeneity of the temperature and stress distributions decreased with decreasing heat transfer coefficient. Since the heat transfer at the die–billet interface corresponds to the thermal conductivity of the die material, it is expected that the die with low thermal conductivity is effective to improve the shape accuracy of the forged billet, regardless of the ram motion control.

Fig. 14 Influence of heat transfer coefficient at die–billet interface on coefficient of variation of shape of inner wall of forged billet after stage (iv). Low coefficient of variation is obtained under low heat transfer coefficient condition, however, the increase of the coefficient of variation is small at \( h_{d,b} \geq 10000 \text{ W/(m}^2\text{·K)} \).

Fig. 15 Influence of heat transfer coefficient at die–billet interface on temperature and equivalent stress distributions in x-z cross-section of billet during stage (i) \((s/stotal = 0.167 \times n_{total} = 6)\). The temperature of the side wall of the billet is high under low heat transfer coefficient condition, and the temperature difference between the outer and inner widths of the billet is small under low heat transfer coefficient condition.
6. Shape accuracy of forged billet in experiment

The validity of the results of the finite element analysis were demonstrated in forging experiment. The forging experiment was carried out with the same conditions described in section 2.2 on the link-type servo press (Komatsu Industrial Corp., H1F45). The experiment was carried out at three times in each forging condition. The load–stroke curves in the forging experiment and finite element analysis is shown in Fig. 16. Good agreement of the load–stroke curves between the forging experiment and finite element analysis was obtained. In addition, the friction between the die and the billet is considered to be almost constant during cup forging because the load was almost constant in the steady-state deformation ($s \geq 3$ mm). Thus the material flow of the billet in the forging experiment is valid for the finite element analysis. Figure 17 shows the experimental results of the x-z cross-sectional shape and the coefficients of variation of the shape and dimension of the inner wall of the forged billet after stage (iv). The inner wall of the forged billet was shrunk to the center direction at the top of the wall, and was overall smaller than the designed dimension ($w_{des} = 16$ mm). From the experimental results of the behavior of the coefficients of variation on the total step number in Fig. 17(b), it is found that the shape and dimensional accuracies are improved by the stepwise ram motion with repetition of the punch advance with short stroke. This is the similar tendency with the results of the finite element analysis (see Fig. 7), however, the accuracies (coefficients of variation) in forging experiment were lower (higher) than the accuracies (coefficients of variation) in the finite element analysis. This may be due to the reduction of the die rigidity caused by the clearance of the dies and the screw fastening of the dies in forging experiment.

From the above results, it is confirmed that the results of the finite element analysis described in section 4 are qualitatively reliable.

![Load–stroke curves in the forging experiment and finite element analysis](image)

Fig. 16 Load–stroke curves in the forging experiment and finite element analysis ($ntotal = 1$, $v_{avg} = 14$ mm/s). Good agreement of the load–stroke curves between the forging experiment and finite element analysis is obtained.

![Experimental results of x-z cross-sectional shape](image)

Fig. 17 Experimental results of x-z cross-sectional shape of inner wall and coefficients of variation of shape and dimension of inner wall of forged billet after stage (iv). Behavior of the coefficients of variation on the ram motion is obtained with the same tendency of the results of the finite element analysis (Fig. 7), however, the coefficients of variation in forging experiment are higher than the coefficients of variation in the finite element analysis.
7. Conclusions

In this study, relationship between the stepwise ram motion (advance stroke, total step number and pause duration) and the shape and dimensional accuracies of the forged billet was investigated in cold cup forging process. The influence of the heat generation of the billet, the elastic deformation of the dies and the heat transfer at the die–billet interface on the accuracies was discussed. The results of the finite element analysis were confirmed to be qualitatively reliable by the demonstration of the forging experiment. The following conclusions were obtained.

1) Shape accuracy of the forged billet is improved by reducing the heterogeneity of the temperature and stress distributions in the forged billet.
2) Repetition of the punch advance with short stroke is effective to reduce the heterogeneity of the temperature and stress distributions in the forged billet.

References


