Simulation of Hammering Hydroforming by Static Explicit FEM

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Recently, tube hydroforming is receiving increasing attention. Knowledge on the process is, however, still insufficient to produce high-quality products in an efficient way. Hammering hydroforming, in which the hydraulic pressure is pulsed synchronously with axial feeding, is an effective method of improving forming ability. However, the factors that cause the improvement are still unclear. In the research reported in this paper, simulations of an automotive component produced by hammering hydroforming have been performed using a static explicit finite-element method code, which was developed in this study. The simulation results showed a good agreement with the experiment, thus validating the hammering hydroforming simulation by the developed code. The factors that improve the forming ability were also investigated by simulation. It was clarified that the hammering forming has the advantage of obtaining enough expansion as well as the regular forming with the lower friction force by using the lower pressure history. Moreover, that roughly the same effect as lowering the friction coefficient could be achieved by the hammering hydroforming.

KEY WORDS: tube hydroforming; hammering forming; static explicit finite-element method; strain path, displacement in the longitudinal direction.

1. Introduction

Recently, from the viewpoint of the preservation of the global environment and impact-damage resistance, product design which satisfies both lightweight structure and high rigidity has become a task which requires special techniques in the automobile industry. Tube hydroforming is one technology that can be used to achieve both targets, as well as to save costs. Recently, this technology has been gaining increasing attention and applications can now be found in the automobile and the aircraft industries.1–4)

Notwithstanding, there are still difficult problems to which conventional technical know-how cannot be applied, such as designing the loading paths of hydraulic pressure and the amount of axial feeding. The capability of the hydroforming process is also largely governed by the outcome of the pre-forming processes. As a result, various types of defects, such as buckling and breakage, may occur if the process parameters are not properly set. These parameters normally are determined by trial and error.

Initiation and growth of buckling are mostly due to excessive material feeding from edges of the tube. Breakage may, however, be caused not only by the lack of material feeding but also by an improper strain path. Therefore, sometimes breakage may occur at unexpected regions of the component.

Fundamental aspects of the tube hydroforming process have been studied experimentally and theoretically.1–14) Through these studies, process characteristics of tube hydroforming have been gradually understood. On the other hand, there are only a few reports on the forming ability of actual engineering parts, from either an experimental or a theoretical point of view.15,16) Although in some studies the tube bending process has been considered as a pre-forming process of tube hydroforming,17) studies on multistage processes are scarce.18,19)

Meanwhile, hammering hydroforming20,21) is known as one of the effective methods of improving the forming ability. In the hammering hydroforming process, the hydraulic pressure is synchronously pulsed with the axial feeding and improvement of the forming ability has been experimentally verified. However, the factors that improve the forming ability are still unclear although several factors are considered, because fundamental studies on the hammering hydroforming are scarce. One of the reasons of this scarcity of studies is that no commercial code can simulate hammering hydroforming process properly.20)

In this paper, simulations of an automotive component produced by hammering hydroforming were performed by a static explicit FEM code, which has been developed in this study. The validity of the developed code for the hammering hydroforming simulation was verified. Moreover, the advantage of the hammering forming has been discussed.

2. Finite Element Formulation

An FEM code for tube hydroforming simulation has been developed22) based on ITAS3D, which is a static explicit FEM code dedicated to sheet metal forming simula-
An updated Lagrangian rate formulation is used to describe the finite deformation. The rate form of the equilibrium equations and boundary conditions are equivalently expressed by the principle of virtual velocity in the form

$$
\int_V \left( \tau^{\delta} : \dot{\varepsilon} + \sigma \cdot \dot{\mathbf{u}} \right) dV - \int_{\Gamma} \dot{p} \dot{v} d\Gamma + \int_{S_G} \dot{f} \dot{v} dS = 0
$$

where $V$ and $S$ denote, respectively, the domain occupied by the body and its boundary at time $t$. $\sigma$ is the Cauchy stress tensor, $L$ is the velocity gradient tensor, and $D$ is the strain rate tensor, which is the symmetric part of $L$. $\delta v$ is the virtual velocity field satisfying the condition $\delta v = 0$ on the velocity boundary. $S_G$ is the part of the boundary $S$ on which the rate of hydraulic pressure $p$ is prescribed. $S_C$ is the part of the boundary $S$ on which the rate of traction $f$ (other than the hydraulic pressure) is prescribed. As for constitutive equations, small strain linear elasticity and large deformation rate-independent work-hardening plasticity are assumed. Hill’s quadratic yield function and the associated flow rule are used. The equation can be written in the form

$$
\tau^e_{ij} = C_{ijkl}^ep_{kl} = C_{ijkl}^e \dot{L}_{ijkl} \quad \text{(2)}
$$

where $C_{ijkl}^e$ are the tangent elastoplastic moduli.

The solution procedure for the formulation stated above follows the standard way of static explicit analysis using the r-minimum strategy.

### 3. Simulation Model

#### 3.1. Suspension Component

In this study, the forming processes of a suspension component of an automobile shown in Fig. 1(a) were simulated. This component is formed through multistage processes: the pre-bending process, the die-closing process, and the hydroforming process. During the hydroforming process, pressure up to 140 MPa and axial feeding up to 200 mm are applied. Ultimately, 43% of maximum expansion is achieved.

In the actual industrial production, this component is formed in a conventional way, in which the pressure is not pulsed, and occasionally a breakage occurs on the inside of a bent region, as shown in Fig. 1(b). The factors that cause the breakage on this region were clarified in a previous report. Recently, the hammering forming has been applied to this component and it was experimentally achieved that the occurring of the breakage could be prevented.

#### 3.2. Simulation Condition

Mild steel was considered as a base material of the tube and the mechanical properties adopted in the simulation are shown in Table 1. For the welding line of the tube, the mechanical properties shown in Table 2 were adopted. Dimensions of the tube are 63.5 mm outer diameter, 1.020 mm length and 2.27 mm wall thickness.

Four-node degenerated shell elements were employed for the tube model with 30 and 150 divisions, respectively in the circumferential and the longitudinal direction. Since the width of the welding line of the tube was about 9 mm, the welding line was modeled by the elements of one line along the longitudinal direction.

In this study, the whole three forming stages were simulated. For the hydroforming process, the simulations of both the hammering forming and the regular forming were carried out. The loading paths employed in the simulation are shown in Fig. 2. The only one difference between the hammering forming and the regular forming comes from the pulsation of the hydraulic pressure applied in the hammering forming. The conditions of the pulsation of hydraulic pressure are summarized in Table 3. As shown in the figure, the hammering forming uses lower pressure history, i.e., the mean pressure of the pulsation of the hydraulic pressure is lower than the regular forming.

### Table 1. Material properties used in the simulation.

<table>
<thead>
<tr>
<th>$E$ (GPa)</th>
<th>$v$</th>
<th>$\sigma_y$ (MPa)</th>
<th>$F$ (MPa)</th>
<th>$n$</th>
<th>$\epsilon_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>0.3</td>
<td>322</td>
<td>583</td>
<td>0.14</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

### Table 2. Material properties for the welding line used in the simulation.

<table>
<thead>
<tr>
<th>$\sigma_y$ (MPa)</th>
<th>$F$ (MPa)</th>
<th>$n$</th>
<th>$\epsilon_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>1200</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

$E$: Young’s modulus. $\nu$: Poisson’s ratio. $\sigma_y$: Yield stress. The true stress-logarithmic plastic strain curve is approximated by $\sigma = F(\epsilon + \epsilon_p)$.
pressure is lower than the regular forming. However, the pressure history shown in Fig. 2 is necessary to obtain enough expansion in the regular forming. Actually, the lack of expansion has been observed when the simulation of the regular forming with the same pressure history as that of the hammering forming has been carried out. Therefore the loading path shown in Fig. 2 was employed.

The Coulomb friction law was applied in the simulation. It has been shown in the previous paper 27) that the simulated result with the friction coefficient \( \mu = 0.05 \) were in good agreement with the experiment for the regular forming. Hence, the friction coefficient \( \mu = 0.05 \) was also employed in the hammering forming simulation. Different friction coefficients, \( \mu = 0.0, 0.05 \) and 0.1, were employed in the regular forming simulation for comparison.

4. Results and Discussions

The results of the pre-bending and the die-closing processes have been described in the previous paper, 27) and hence are not repeated here.

4.1. Thickness Strain Distribution

Figure 3 shows the simulated thickness strain distributions of the component. Although the two simulated results give identical shapes, they clearly present different thickness strain distributions. The component can be divided into three regions with regard to the trend of the difference as shown in the figure. The first region (region I) is around the edge of the tube and the thickening decreased in the hammering forming compared to that of the regular forming. To examine more detail, the thickness strain distribution of the cross section A, which is on the edge, is shown in Fig. 4(a). About 40% of thickening occurred in the regular forming, while 30% in the hammering forming and a good agreement was seen between the simulation and the experiment.

The second region (region II) neighbors on the section of maximum expansion and almost no difference in the thickness strain distribution was seen. The thickness strain distribution of the cross section B, which is on the section of...
maximum expansion, is shown in Fig. 4(b). The thickness strain distributions were almost identical regardless of the forming conditions in the experiment, although some difference was seen between the both simulated results.

The third region (region III) is the region between the section of maximum expansion and the bent region and the thinning decreased in the hammering forming. The thickness strain distribution of the cross section C, which corresponds to an expansion of 33%, is shown in Fig. 4(c). A small but clear difference was seen between the result of the regular forming and that of the hammering forming, and a good agreement was seen between the simulation and the experiment.

As mentioned in the introduction, several factors can be thought of as improving the forming ability, such as the change of friction coefficient itself. Some of them may require special formulations, which are not necessary in the regular forming process and are not considered in this study. This might cause the difference between the simulated result and the experiment. However, the tendency of the distribution was well reproduced in the simulations and it confirms the validity of applying the developed static explicit FEM code for the hammering forming simulation. Moreover, in the hammering forming, it became clear that the thickening in region I decreased and as a result the thinning decreased in region III.

4.2. Strain Path

To see the effect of the hammering forming on the deformation process and the thickness distribution in detail, strain paths on several different points are examined. As previously pointed out, the component can be divided into the three regions with regard to the change of the thickness strain distribution. Therefore, the nodes shown in Fig. 5(a) were selected to represent the deformation on each region. Here, the region I was neglected because almost no expansion occurred, while node c was selected because this is the point where the breakage occurred. In the following results, the theoretical forming limit by Stören and Rice28) and the results of the regular forming with \( \frac{m}{H} = 0.05 \) and 0.1 were also included for comparison.

Figure 5(b) shows the strain paths on node a, which is in the cross section B shown in Fig. 4. The result of the hammering forming and that of the regular forming with \( \mu = 0.05 \) were identical, and still the differences in the strain paths were small, regardless of the forming conditions. The generation of the longitudinal compressive strain is achieved by the axial feeding, and these results point out that the effect of the axial feeding on this region remained unchanged regardless of the forming conditions. This is because this region is close to the edge. As a result, the thickness strain remains the same as shown in Fig. 4(b).

Figure 5(c) shows the strain paths on node b, which is in the cross section C. The effect of the pulsation of the hydraulic pressure in the hammering forming was slightly observed and the longitudinal compressive strain increased compared to that of the regular forming with \( \mu = 0.05 \). This increase in the longitudinal compressive strain was achieved by the increase of the material feeding by the axial feeding from the edge, and as a result the thinning decreased as shown in Fig. 4(c). This result shows that the in-
fluence of the material feeding on the strain path on this region became slightly larger than that on node $a$. Moreover, since the longitudinal compressive strain increased along with the decrease of the friction coefficient as shown in the figure, it can be said that the same effect as lowering the friction coefficient was achieved in the hammering forming.

Figure 5(d) shows the strain paths on node $c$, which is situated in the neighborhood of the breakage zone. The influence of the pulsation of the hydraulic pressure became yet larger than that on node $b$ and the longitudinal compressive strain increased more. At this point, about 24% of thickness strain occurred in the regular forming, while 19% in the hammering forming. This shows that the breakage became harder to cause in the hammering forming. In addition, the difference of the strain path with regard to the change of the friction coefficient also became large and this shows that this part was sensitive to the change of the frictional condition.

By summarizing the above, it became clear that, in the hammering forming, the thinning around the breakage zone decreased and the breakage became harder to cause. The reason of the decrease of the thinning was the increase of the longitudinal compressive strain and this increase was achieved by the increase of the material feeding from the edge.

### 4.3. Displacement in the Longitudinal Direction

As described in the Sec. 3.2, the hammering forming uses lower pressure history and this can be considered to be a factor of the material feeding increase in the hammering forming. Therefore, the influence of friction force to the material feeding is investigated.

Figure 6 shows the relationship between the hydraulic pressure and the amount of the displacement in the longitudinal direction at node $b$. Node $b$ was selected because the effect of the pulsation of the hydraulic pressure was clearly seen in the strain path. In this figure, the direction of axial feeding from the left edge was defined as the positive, as shown in Fig. 6(a).

Figure 6(b) shows the result of the hammering forming with $\mu=0.05$ and that of the regular forming with $\mu=0.05$. When the hydraulic pressure was in the range of 0–40 MPa, both amounts of the displacement $L$ were identical. Subsequently, the pulsation of the hydraulic pressure started in the hammering forming and the amount of the displacement in the hammering forming became larger than that in the regular forming. The pulsation of the hydraulic pressure finished around 60 MPa and the difference no longer increased. This result shows that a larger amount of the displacement was achieved by the hammering forming, and moreover, the difference increased during the pulsation of the hydraulic pressure.

On the other hand, Fig. 6(c) shows the results in the case of $\mu=0.0$. In this case, both amounts of the displacement $L$ were almost identical until the end of the process and the difference noticed in the case $\mu=0.05$ was no longer observed. Some difference occurred around 60 MPa, but this difference came from the difference of the loading path. This demonstrates clearly that the difference in the amount of the displacement in the case of $\mu=0.05$ was achieved by the reduction of the friction force during the pulsation of the hydraulic pressure.

This result denotes that it is better to use the lower pressure history to obtain larger amount of the displacement. However, as described before that the pressure history shown in Fig. 2 is necessary to obtain enough expansion in the regular forming. On the other hand, the hammering forming gives enough expansion as well as the regular forming. The reason of this result can be considered that the maximum pressure in the pulsation makes the same pressure history as that of the regular forming. Hence, it can be concluded from these results that the hammering forming has the advantage of obtaining enough expansion as well as the regular forming with the lower friction force by using the lower pressure history.

### 5. Conclusions

Simulations of a hydroformed automotive component
with hammering hydroforming by a static explicit FEM code developed in this study have been performed. And the advantage of the hammering forming was discussed. The results obtained in this study can be summarized as follows.

1) The simulation of the hammering hydroforming process showed a good agreement with the experiment and has reproduced the thickness strain distribution well. This confirmed the validity of the developed static explicit FEM code for the hammering hydroforming simulation.

2) The hammering forming has the advantage of obtaining enough expansion as well as the regular forming with the lower friction force by using the lower pressure history.

3) The hammering forming has roughly the same effect as lowering the friction coefficient.

As described in the introduction, several factors other than the reduction of friction force can also be considered as improving the forming ability. Hence, more investigations on the other factors are to be performed to see the actual advantages of the hammering forming in the future works.

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