Determination of back-pressure profile and slide motion of servo press in cold forging using sequential approximate optimization

Satoshi KITAYAMA*, Tsubasa HIGUCHI**, Masahiro TAKANO*** and Akio KOBUYASHI****

* Advanced Manufacturing Technology Institute, Kanazawa University
Kakuma-machi, Kanazawa-shi, Ishikawa 920-1192, Japan
E-mail: kitayama-s@se.kanazawa-u.ac.jp
** Graduate School of Natural Science and Technology, Kanazawa University
Kakuma-machi, Kanazawa-shi, Ishikawa 920-1192, Japan
*** Industrial Research Institute of Ishikawa
2-1, Kurasuki, Kanazawa-shi, 920-8203, Japan
**** KAGA INC.
Ota Ni-140, Tsubata-cho, Kaizoku-gun, Ishikawa 929-0345, Japan

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1. Introduction

Cold forging is a typical manufacturing technology to produce various mechanical components such as gear, airfoil blades and connecting rods. The preform design has an influence on the dimensional accuracy of product, and one of the major issues in cold forging is to determine the preform shape minimizing the unfilled volume. The determination of preform (or die) shape through experiment is time-consuming, and numerical simulation is so widely used.

Zhao et al. performed a 2D die shape optimization using sensitivity analysis (Zhao et al., 1997), in which the die shape was optimized so as to minimize the difference between the actual and the desired final forging shape. Preform optimization using the evolutionary structural optimization (ESO) has been used, and Shao et al. proposed a strain-based element addition and removal criterion and the proposed approach was applied to 2D preform optimization (Shao et al., 2014). In 2D preform shape optimization, the computational cost is not so intensive. However, 3D forging simulations using finite element method (FEM) are much complex and intensive. Consequently, it is difficult to perform 3D preform optimization using the sensitivity analysis or the ESO that require a large number of simulations. In contrast, response surface method (RSM) is much useful to resolve this issue, and Thiagarajan and Grandhi adopted the RSM and the basis vector method for 3D preform shape optimization (Thiagarajan and Grandhi, 2005). Another advantage using the RSM is to be able to handle the process parameters in cold forging such as forward push force, friction coefficient, axial feed and back-pressure. Among them, back-pressure is one of the important process parameters for high product quality, and...
Deng et al. investigated the effect of back-pressure on unfilled defect of a rib-web part (Deng et al., 2018). In their paper, it was reported that the unfilled defect was successfully solved by the back-pressure control and the control was also effective to the metal flow distribution. Okada et al. determined an optimal back-pressure profile so as to minimize the unfilled area and the forming energy simultaneously (Okada et al., 2015).

Recently, servo press that can control the slide motion as well as the back-pressure during forging has attracted attention for high product quality without losing productivity. Osakada investigated various applications to metal forming using servo press, and pointed out that it was important to determine both the slide motion and the back-pressure for the high product quality (Osakada, et al., 2011). The effect of slide motion on product quality was also investigated by Son et al. (Son et al., 2013), but the slide motion was completely determined by a trial-and-error method. It is preferable to determine the back pressure and the slide motion with an intelligent manner for improving product quality.

In this paper, optimal back-pressure profile and the slide motion considering product quality and productivity in cold forging are simultaneously determined. DEFORM3D is used for the numerical simulation, and a multi-objective design optimization is performed to determine them. Numerical simulation is so intensive that sequential approximate optimization (SAO) using radial basis function (RBF) network is adopted (Kitayama et al., 2011). The pareto-frontier is identified, and the optimal back-pressure profile and the slide motion are determined. Based on the numerical result, the experiment using servo press (H1F200-2, Komatsu Industries, Corp.) is conducted. The validity of the proposed approach is examined through the experiment.

2. Target product and numerical simulation model

2.1 Overview of product, production process and requirement

A small product is selected, and the overview is shown in Fig. 1. The billet of the diameter and the height are set to 14.00 mm and 4.00 mm respectively, and the height of the product after the forging is 9.00 mm. Figure 2 shows the half section of the product (left hand) and the view from z-direction (right hand).

![Fig. 1 Target product and the overview](image1.png)

The requirement to the product is shown with red in Fig. 2, from which it is found that highly accurate bottom thickness is required. Machining that can easily meet the requirement is conventionally used to produce the product, but the productivity is too low and about 80% materials are wasted. In contrast, the forging can drastically improve the productivity as well as the material yield, but it is difficult to meet the dimensional requirement.

![Fig. 2 Dimensional requirement of target product (half section and bottom view)](image2.png)
2.2 Numerical simulation model

Considering the symmetry of the product, one-fourth numerical simulation model shown in Fig. 3 is constructed, in which the counter punch and the die are fixed, and the upper punch drops to the negative z-direction. The total stroke of the upper punch is 3.02 mm and the back-pressure is applied to the outer punch to the positive z-direction. The material of billet is aluminum (A5052), and the material property is listed in Table 1. Rigid-plastic solid element is used for the billet, and the initial number of finite elements is set to 9176. The share friction coefficient 0.4 between the billet and all rigid bodes is used in the numerical simulation. The stress-strain curve at various strain rate dependency shown in Fig. 4 that has been obtained via several experiments is also used in the numerical simulation.

![Numerical simulation model with forging process](image)

| Table 1 Material property of A5052 |
|-----------------------------------|
| Density [kg/mm³] | 2.68 x 10⁶ |
| Young’s modulus [MPa] | 689 x 10² |
| Poisson’s ratio (ν) | 0.33 |

3. Design optimization for back-pressure profile and slide motion

As described in introduction, the back-pressure and the slide motion have been determined by a trial-and-error method. In this paper, a multi-objective design optimization which is formulated in Eq. (1) is adopted to determine them.

\[
(f_1(x), f_2(x), \ldots, f_K(x)) \rightarrow \min \\
x = (x_1, x_2, \ldots, x_n) \in R
\]

where \(f_i(x)\) is the \(i\)-th objective function to be minimized, \(K\) is the number of objective functions, \(x\) is the design
variables belonging the feasible region $R$, and $n$ is the number of design variables (Miettinen, 1998).

### 3.1 Design variables

First, let us explain the back-pressure profile using Fig. 5(a). To determine the back-pressure profile, as we have already performed (Kitayama et al., 2017), the total stroke of 3.02 mm is divided into three sub-stroke steps. The back-pressure of each sub-stroke step ($P_1$, $P_2$, and $P_3$ in Fig. 5(a)) is taken as the design variables. Next, let us explain the slide motion using Fig. 5(b), in which the dashed curve line represents the maximum slide velocity (SV) of the servo press. The SV is determined by the ratio to the maximum SV (Zhuang et al., 2016), and this value called the SV ratio is the process parameter to determine the slide motion. As shown in Fig. 5(b), the total stroke is divided into three sub-stroke step, and the SV ratio of each sub-stroke step ($V_1$, $V_2$, and $V_3$ in Fig. 5(b)) is taken as the design variables. Finally, the design variables is given by $x = (P_1, P_2, P_3, V_1, V_2, V_3)^T$, and the lower and upper bounds are given by Eq. (2).

$$5.0 \leq P_1, P_2, P_3 \leq 25[kN] \quad 10 \leq V_1, V_2, V_3 \leq 50[\%]$$  

(2)

Fig. 5 Design variable for back-pressure profile and slide velocity

It is preferable to consider the number of partitions as the design variables, and the design optimization problem is then formulated as the mixed integer programming. However, the mixed integer programming is much difficult to find the optimal solution (Kitayama, et al., 2006). Then, for the simplicity, the number of partitions is fixed in this paper.

### 3.2 Objective functions

Two objective functions are considered for high productivity and product quality. The processing time that the upper punch reaches at bottom dead center is taken as the first objective function $f_1(x)$ to be minimized. As shown in Fig. 6, the slide velocity in this paper is given by the solid curve line. Then, the following procedure is then used to numerically evaluate the processing time.

(STEP1) The solid curve line is discretized along the stroke axis, and is locally represented by linear approximation as shown in Fig. 6. Here, let $NDP$ be the number of discretized points. $l_i (i = 1, 2, \cdots, NDP)$ denotes the $i$-th die position along the stroke axis.

(STEP2) The upper punch velocity at the all discretized points is calculated, which is denoted by $v_i (i = 1, 2, \cdots, NDP)$. The illustrative example is shown in Fig. 6, in which $T_i$ represents the time during the upper punch proceeds from $l_i$ to $l_{i+1}$. The time $T_i$ is calculated by the following equation.

$$T_i = \frac{2(l_{i+1} - l_i)}{v_{i+1} + v_i} \quad i = 1, 2, \cdots, NDP - 1$$  

(3)

where $l_0 = 0$ $l_{NDP} = l_{max} (= 3.00)$ $v_{min} = 0$.

(STEP3) We assume that the processing time is given by the sum of $T_i$, and the following objective function is minimized for high productivity:

$$f_1(x) = \sum_{i=1}^{NDP-1} T_i$$
Next, let us consider the product quality. As shown in Fig. 2, the highly accurate bottom thickness is required. It will be possible to evaluate the bottom thickness when all dies are modelled as the elastic body in the numerical simulation. Therefore, the all dies are deformed during the forging, and the distance between the upper punch and the counter punch is evaluated as the bottom thickness. However, the computational cost is much high. To avoid this situation, all dies are often modelled as the rigid body in forging simulation (Zhou et al., 2014). Since the upper and counter punch are modelled as the rigid body in the numerical simulation model, it is impossible to numerically evaluate the bottom thickness using the distance between the upper punch and the counter punch. As the alternative to evaluate the bottom thickness, we assume that the surface hardening will make the bottom flat. To make the bottom flat, the equivalent strain on the bottom should be distributed uniformly as much as possible. In other words, the distribution of equivalent strain on the bottom is minimized in order to make the bottom flat. Therefore, the second objective function is given by Eq. (5).

\[
f_2(x) = \min \frac{\sum_{i=1}^{n_{elm}} (\xi_i - \xi_{ave})^2}{n_{elm}}
\]

where \(\xi_i\) is the \(i\)-th equivalent strain on the bottom, \(\xi_{ave}\) is the average equivalent strain on the bottom, and \(n_{elm}\) is the number of finite elements on the bottom.

### 4. Numerical procedure to determine back-pressure profile and slide motion

The numerical procedure of SAO using RBF network is summarized in this section. See the references (Kitayama et al., 2011; Miettinen, 1998) for the detailed procedure of the SAO and the weighted lp norm method.

**STEP0:** The latin hypercube design (LHD) is used to generate the initial sampling points.

**STEP1:** Numerical simulation is carried out to evaluate the objective functions at the sampling points.

**STEP2:** Response surface is constructed to two objective function.

**STEP3:** The weighted lp norm method is used to determine a set of pareto-optimal solutions with various weights.

**STEP4:** If the terminal criterion is satisfied, the SAO algorithm will be terminated. Otherwise, go to STEP5.

**STEP5:** To improve the pareto-frontier, the set of pareto-optimal solutions obtained in STEP3 is added as the new sampling points. Then, return to STEP1.

The error at the pareto-optimal solutions is adopted as the terminal criterion. If the error is within 5%, the SAO will be terminated. The flow of SAO is shown in Fig. 7.
5. Numerical and experimental result

5.1 Numerical result

Twenty initial sampling points are generated by the LHD, and the pareto-frontier shown in Fig. 8 has been identified, in which the distribution of equivalent strain on the bottom is also shown. The optimal back-pressure profile and slide motion at points A, B and C in Fig. 8 is shown in Fig. 9 with the forging process, in which the solid line represents the optimal back-pressure profile and the dashed curve line represents the optimal slide velocity. The forging process at three sub-stroke steps (1.00mm, 2.00mm and 3.02mm) is also shown in this figure.

First, let us consider point A. As shown in Fig. 9, the product is produced with the high slide velocity during the forging, and this results in the short processing time. On the other hand, the low back-pressure is applied at the first sub-stroke step, and after that, the high back-pressure is applied till the end of forging. As shown in Fig. 8, this leads to the high distribution of equivalent strain of the bottom.

Next, let us consider point C. Unlike the slide velocity at point A, the billet is formed with the high slide velocity (SV ratio: 49.8%) at the first sub-stroke step. After that, the slide velocity gradually decreases (the SV ratio is 39.3% at the second sub-stroke step, and the SV ratio is 33.4% at the final sub-stroke step). As the result, the long processing time is required. The low back-pressure is applied at the first sub-stroke step and the high one is applied at the second sub-stroke step. Unlike the back-pressure at point A, the back-pressure at the final sub-stroke step decreases. The lower back-pressure can improve the material flow, and this makes the distribution of equivalent strain of the bottom more uniform.

Finally, let us consider point B. Like the slide velocity at point C, the high slide velocity is used at the first sub-stroke...
step. Then, the slide velocity gradually decreases. However, the higher slide velocity at the final sub-stroke step is used at the final sub-stroke step, compared with the slide velocity at point C. The back-pressure profile is similar with the one at point C. Compared with other two points, as shown in Fig. 8, the processing time and the distribution of equivalent strain are relatively well-balanced.

5.2 Experimental result

Based on the numerical result, the experiment at points A, B and C in Fig. 8 is carried out. In the experiment, the servo press (H1F200-2, Komatsu Industries, Corp.) is used, and the numerical result is directly inputted into the servo press. The result is shown in Fig. 10, in which the dashed line represents the numerical result and the solid one represents the experimental result. Due to the short processing time and stroke, the optimal back-pressure profile and slide velocity in the experiment does not always coincide on the numerical result. However, the product is well produced. In the product, as shown in Fig. 2, the highly accurate bottom thickness is required. Then, seven points on the bottom shown in Fig. 11 is selected to evaluate the bottom thickness. The result is listed in Table 2, in which \( h_{\text{max}} \) and \( h_{\text{min}} \) represent the maximum and minimum bottom thickness respectively and \( STD \) represents the standard deviation of the bottom thickness at seven evaluation points. This table indicates that, when the difference \( (h_{\text{max}}-h_{\text{min}}) \) is less than the tolerance \( (0.026) \), the dimensional requirement is satisfied. It is clear from Table 2 that the bottom thickness produced by the proposed approach can meet the requirement. In addition, the standard deviation of the bottom thickness is much small, and this indicates that Eq. (5) is valid to make the bottom flat. Through the experimental result, the validity of the proposed approach has been confirmed.
Fig. 10 Experimental result at points A, B and C

Fig. 11 Evaluation points of the bottom thickness
Table 2 Difference of maximum and minimum bottom thickness and standard deviation of bottom thickness

|        | $h_{max} - h_{min}$ [mm] | STD    |
|--------|--------------------------|--------|
| Point A| 0.009                    | $3.21 \times 10^{-3}$ |
| Point B| 0.008                    | $2.61 \times 10^{-3}$ |
| Point C| 0.010                    | $3.23 \times 10^{-3}$ |

6. Concluding remarks

This paper determined the optimal back-pressure profile and slide motion of servo press using the SAO. A small product which required the highly accurate bottom thickness was selected as the case study. For high productivity, the processing time was minimized, whereas the distribution of equivalent strain on the bottom was minimized for high product quality. Therefore, the multi-objective optimization was performed to determine the optimal back-pressure profile and slide motion. The pareto-frontier between the objectives was identified through the numerical simulation. Based on the numerical result, the experiment was carried out. Through the experimental result, the product met the dimensional requirement, and consequently the validity of the proposed approach has been confirmed.

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