

Chapter 2

Process/Shape-Decomposition Modeling for Deformation Force Estimation

Abstract The deformation force of a forging is crucial for manufacturing high-quality products and for managing the machine's physical condition. In this chapter, a process/shape-decomposition modeling method is presented to estimate this deformation force in the complex forging process. The complex forging process is first decomposed into a group of simple sub-processes using system knowledge. In each sub-process, the complex geometric shape is then decomposed into many easily modeled sub-units, upon which the deformation force model of each sub-unit is built as the sub-model. All sub-models are further integrated to form a global deformation force model for the whole forging process. The continuity of this global model are also considered and guaranteed.

2.1 Introduction

A high-quality forging usually requires the work plate to have a desirable position and velocity response [1–3]. The control of the position and velocity of the work plate depends entirely on the deformation force model of the forging [3]. This is because the deformation force model reflects the relationship of the deformation of a forging to its deformation force, and this force can determine the required pressure offered by the hydraulic actuator and, thus, further determine the output of the controller. The more accurate this deformation force model is, the easier it is to control the forging process. Therefore, the deformation force model is crucial in the high-quality forging.

However, as indicated in Fig. 2.1, the deformation processes are usually very complex due to the following reasons:

- (1) The forging process is complex [4–8] due to
 - Complex rheological behavior of the metal forging and nonlinear metal flow in all directions;
 - This deformation process is nonlinearly related with material property, stress, stress ratio and temperature;

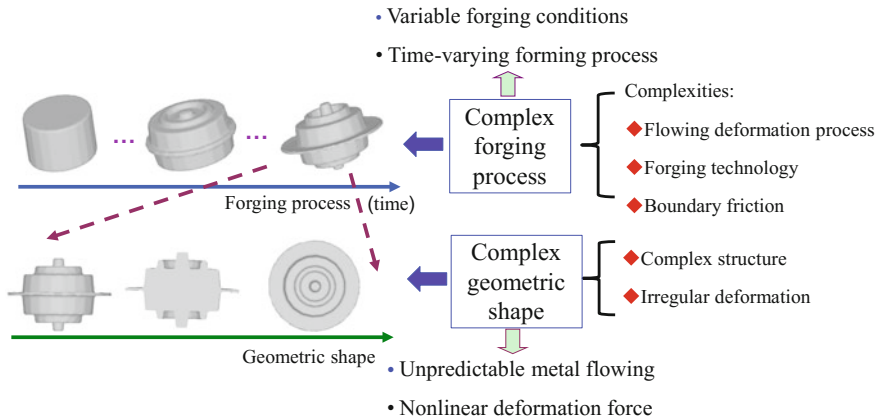


Fig. 2.1 Complex forging process

- Complex boundary constraints from the dies;
 - Complex friction behavior between the forging and the dies.
- (2) The forging has a complex and time-varying geometric shape, which also causes a complex deformation force since the deformation force of the forging depends on its deformation.
 - (3) The deformation force involves many parameters that are difficult to obtain, such as friction and boundary conditions.
 - (4) The deformation force cannot be measured directly in the experiment.

All the aforementioned factors bring a great challenge to modeling of the deformation force, which often makes the deformation process difficult to control.

Many studies have contributed to the modeling of the deformation force by analytical methods and finite element methods. A nonlinear model numerically solved by the finite element method can be used in the design of the HPM [9–11]. However, it must incorporate all boundary conditions and forging conditions, which can be difficult to obtain. It is also difficultly applied to design the controller of the HPM due to their complexity and large computational costs. The analytical modeling methods mainly include the principal stress method [12–14], the slip-line method [15–17], the upper bound method [18–20], and the variational method [21]. These methods must know all conditions of the forging process, including the material parameters, shape parameters and boundary conditions. However, obtaining all these conditions is often difficult. Moreover, they paid less attention to the complex forging process with the complex geometric shape of the forging. Furthermore, in the design of the controller, this deformation force is often represented by a linear model produced through simulation or the experience of the experts [22, 23]. The linear model is often coarse due to neglect of the nonlinear dynamics, especially when the production requires a large-scale forging. Thus, an

effective modeling method is still necessary to be developed for the deformation force estimation in a complex forging process.

In this chapter, a process/shape-decomposition modeling method is developed for the deformation force estimation in a complex forging process. The complex forging process is first decomposed into a group of simple sub-processes using system knowledge. Each sub-process represents one kind of system feature, such as the free upsetting stage, the filling cavity stage or the die kissing stage. In each sub-process, the complex geometric shape is then decomposed into many easily modeled sub-units, upon which the deformation force model of each sub-unit is built as the sub-model. All sub-models are further integrated to form a global deformation force model for the whole forging process. The continuity of this global model, between two adjacent sub-units and between two adjacent sub-processes, are also considered and guaranteed. Its unknown parameters are identified using deformation force data, which can be indirectly obtained via the motion model of the hydraulic actuator. Experiments and simulations finally demonstrate and test the effectiveness of the proposed modeling method.

2.2 Process/Shape-Decomposition Modeling Method

In this section, a novel process/shape-decomposition modeling method is proposed to estimate the deformation force in the complex time-varying forging process, as indicated in Fig. 2.2 with several key points. It first decomposes the whole forging process into many sub-processes, upon which the complex geometric shape in each sub-process is then decomposed into many easily modeled sub-units. The global deformation force model of the whole forging process is further derived by integrating all sub-unit models. The continuity of this global model, between two adjacent sub-units and between two adjacent sub-processes, are also considered and

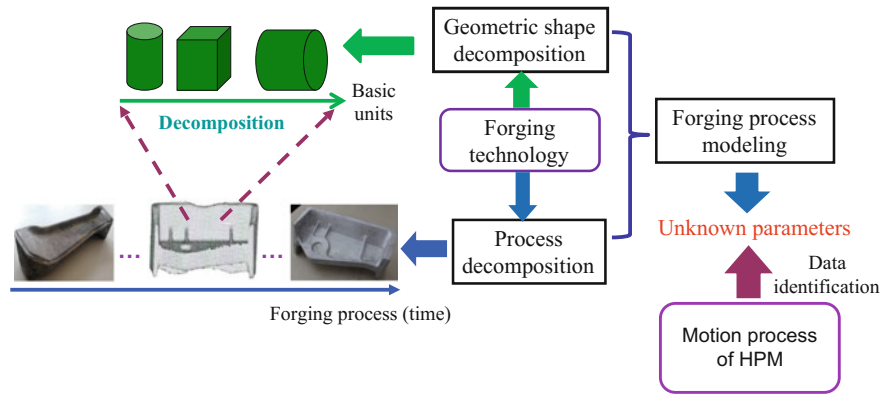


Fig. 2.2 Process/shape-decomposition modeling method

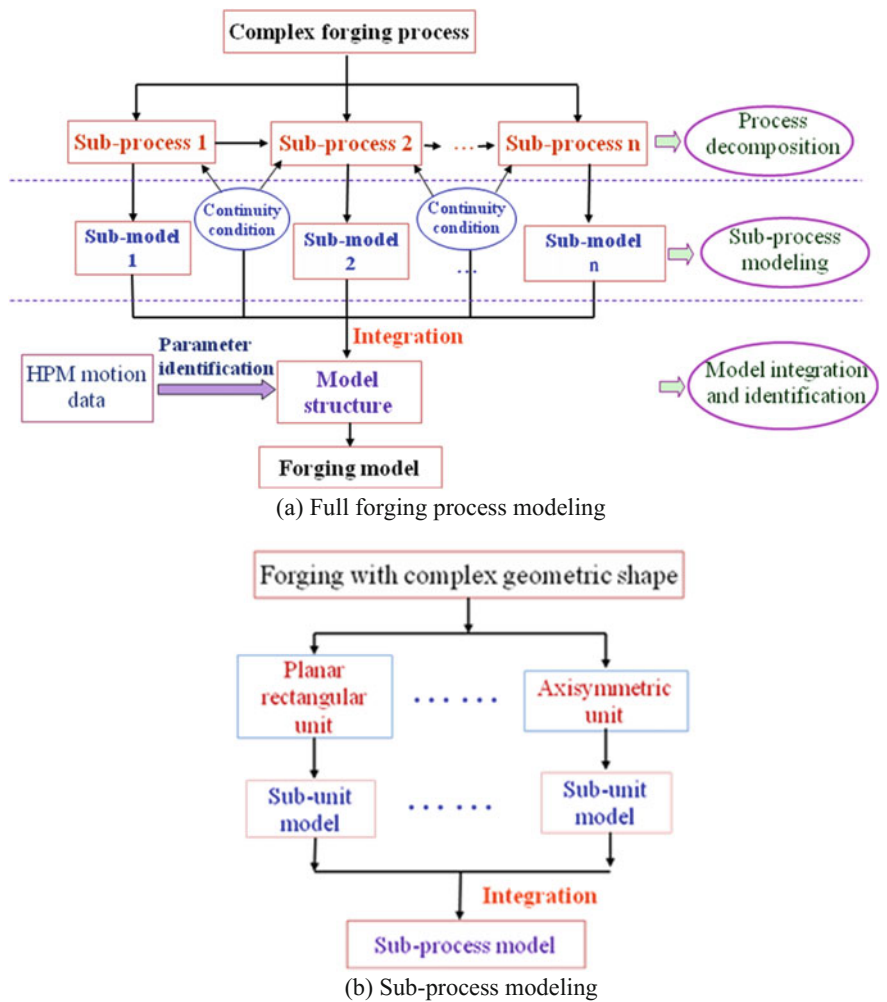


Fig. 2.3 Modeling configuration

guaranteed. Finally, unknown parameters in this global model are identified by using data of forging process.

A detailed configuration of the proposed method is shown in Fig. 2.3. It involves the following key points:

- **Process decomposition:** The complex forging process is decomposed into a group of simple sub-processes using system knowledge. Each sub-process represents one kind of system feature, such as the free unsetting stage, the filling cavity stage or the die kissing stage. In this way, the complex modeling task of

the original forging process is decomposed into a series of simple and easily realized sub-modeling tasks.

- Geometric shape decomposition based sub-process modeling: In each sub-process, the complex geometric shape of the workpiece is then decomposed into many easily modeled units, such as the planar rectangular element and the axisymmetric element, as shown in Fig. 2.3b. The deformation force model of each sub-unit is then built. Finally, the model structure of this sub-process is determined by integrating the deformation forces of all sub-units. The continuity between two adjacent sub-units in each sub-process is also considered and guaranteed.
- Model integration: the models of all sub-processes are integrated with consideration of the continuity condition between two adjacent sub-processes to construct a global deformation force model.
- Parameter identification: in simulation, the deformation force data can be directly used to identify unknown parameters in the global model. While in the practical forging, since the deformation force data cannot be measured directly, the global model is inserted into the motion model of the hydraulic actuator, upon which its unknown parameters are identified online using deformation force data that are indirectly derived from the motion model. This makes the deformation process of a forging capable of real-time prediction and control.

The advantage of this presented method is that the process complexity is decomposed into many sub-processes and the modeling task is also shared by a group of simple sub-modeling tasks. Thus, it can easily and effectively achieve the satisfactory modeling performance for the complex forging process. It also makes the deformation process of a forging capable of real-time prediction and control.

2.2.1 Process/Shape-Decomposition and Sub-process Modeling

The forging process described in Fig. 2.4 is used as an example to explain this modeling method. Since the length of this forging is much greater than its width and height, the user may assume that there is no deformation in the length direction [4, 5]. This means that this deformation occurred only on one plane, as shown in Fig. 2.4. According to the proposed modeling method, the whole forging process is divided into three sub-processes. Then, according to the geometric shape of each sub-process and the force analysis in Fig. 2.4 (arrow stands for force direction in the upper four figures), each sub-process is divided into many sub-units, such as the planar rectangular unit ABCD as the sub-unit 1 and the planar rectangular unit DCFE as the sub-unit 2 at the sub-process 1 (as shown in the down four figures). The details of the sub-process modeling and the model integration are presented below.

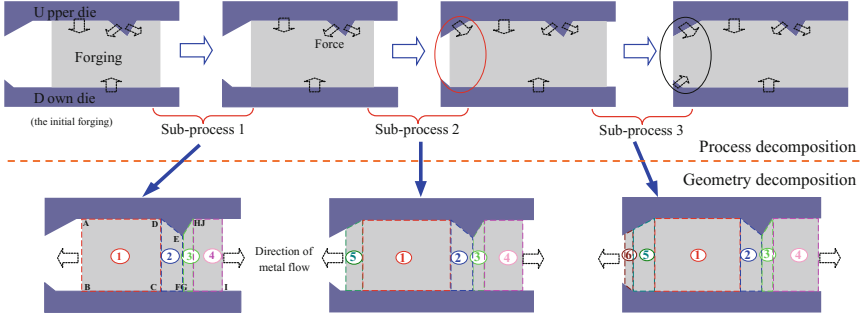


Fig. 2.4 Process decomposition and geometric shape decomposition

A. Sub-process modeling

Due to the similarity between sub-processes, modeling of the sub-process 1 is taken as an example to explain modeling of the sub-processes. The forging at the process 1 is divided into four planar rectangular sub-units as shown in Fig. 2.4. Its boundary conditions are represented as $\sigma_1^{AB} = 0$ and $\sigma_1^{IJ} = 0$. Then, the deformation force of each sub-unit is derived according to the following order: the sub-unit 1, the sub-unit 2, the sub-unit 3, and the sub-unit 4. Two typical sub-units, the sub-units 1 and 2 at the sub-process 1, are taken as an example to explain modeling of the sub-units.

(a) Modeling of the sub-unit 1

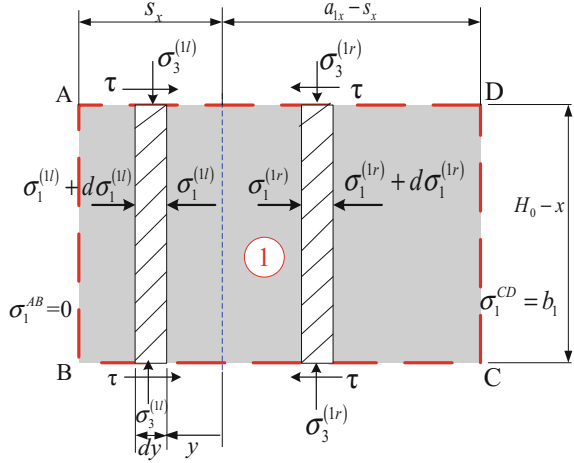
The neutral plane is usually used in the principal stress method [4, 5]. It is to keep the continuity of the normal stresses under given boundaries. Based on this neutral plane, it is easy to derive the deformation force model of this sub-unit. The detailed derivation will be presented below.

At the sub-unit 1, the neutral plane is regarded at the distance equal to s_x from the planar AB at the present height. This distance s_x will be decided subsequently. Then, two micro-units with the width of dy on both sides of the neutral plane are taken, as shown in Fig. 2.5. On the left side of the neutral plane, according to the force balance, the total force in the y direction can be written as follows:

$$\sigma_1^{(l)}(H_0 - x)L - \left(\sigma_1^{ll} + d\sigma_1^{(ll)} \right)(H_0 - x)L - 2\tau Ldy = 0 \quad (2.1)$$

Here, $\sigma_1^{(l)}$ is the normal stress in the y direction, H_0 and x are the initial height of the raw forging and the deformation value in the height direction respectively, L is the length, and τ is the shear stress. The superscript (1l) represents the left side of the neutral plane at the sub-unit 1.

Fig. 2.5 Stress analysis of the sub-unit 1 at the stage 1



The above equation produces the following:

$$d\sigma_1^{(ll)} = -2\tau \frac{dy}{H_0 - x} \quad (2.2)$$

The integral of Eq. (2.2) gives the following:

$$\sigma_1^{(ll)} = -2\tau \frac{y}{H_0 - x} + c \quad (2.3)$$

The following boundary condition exists:

$$\sigma_1^{AB} = \sigma_1^{(ll)}(y = s_x) = 0 \quad (2.4)$$

Inserting Eq. (2.3) into Eq. (2.4) results in:

$$c = 2\tau \frac{s_x}{H_0 - x} \quad (2.5)$$

Inserting Eq. (2.5) into Eq. (2.3), the following is satisfied:

$$\sigma_1^{(ll)} = 2\tau \frac{s_x - y}{H_0 - x} \quad (2.6)$$

According to the plastic conditions of the plane problem, the following is true [4, 5]:

$$\sigma_3^{(ll)} - \sigma_1^{(ll)} = \frac{2}{\sqrt{3}} \sigma_s \quad (2.7)$$

Here, σ_s is the yield stress. The stress σ_s is dependent on the material, the strain ε , the strain ratio $\dot{\varepsilon}$, and the temperature T . For example, the Rosserd model is usually used to represent this model for an aluminum alloy material under the isothermal forging:

$$\sigma_s = C\varepsilon^N\dot{\varepsilon}^M + K_f \quad (2.8)$$

Here, C , N , M , and K_f are the material parameters.

The friction condition may be written as the following [4, 5]:

$$\tau = \mu_s \sigma_s \quad (2.9)$$

Here, μ_s is the friction coefficient.

In this way, from (2.6), (2.7) and (2.9), the normal stress at the contact region can be rewritten as follows:

$$\sigma_3^{(1l)} = 2\mu_s \sigma_s \frac{s_x - y}{H_0 - x} + \frac{2}{\sqrt{3}} \sigma_s \quad (2.10)$$

On the right side of the neutral plane, let the boundary condition $\sigma_1^{CD} = b_1$, that is

$$\sigma_1^{(1r)}(y = a_{1x} - s_x) = b_1 \quad (2.11)$$

Here, a_{1x} is the real-time width of the sub-unit 1.

Similar to the derivation of $\sigma_3^{(1l)}$, its stress $\sigma_3^{(1r)}$ can be derived as follows:

$$\sigma_3^{(1r)} = 2\mu_s \sigma_s \left(\frac{a_{1x} - s_x - y}{H_0 - x} \right) + \frac{2}{\sqrt{3}} \sigma_s + b_1 \quad (2.12)$$

According to the continuity of the principal stress, $\sigma_3^{(1r)}$ and $\sigma_3^{(1l)}$ should be the same at the neutral plane. Thus, we have:

$$2\mu_s \sigma_s \frac{s_x}{H_0 - x} + \frac{2}{\sqrt{3}} \sigma_s = 2\mu_s \sigma_s \frac{a_{1x} - s_x}{H_0 - x} + \frac{2}{\sqrt{3}} \sigma_s + b_1 \quad (2.13)$$

From Eq. (2.13), we have

$$s_x = \frac{a_{1x}}{2} + b_1 \frac{H_0 - x}{4\mu_s \sigma_s} \quad (2.14)$$

Thus, the position of the neutral plane is obtained.

Then, by integrating the stress of the sub-unit 1, the deformation force P_{11} of the sub-unit 1 on the contact region is easily derived as follows:

$$\begin{aligned}
 P_{11} &= \int_0^{s_x} \sigma_3^{(1l)} L dy + \int_0^{a_{1x}-s_x} \sigma_3^{(1r)} L dy \\
 &= L \times \left[\frac{a_{1x}^2 - 2a_{1x}s_x + 2s_x^2}{H_0 - x} \mu_s \sigma_s + \frac{2}{\sqrt{3}} \sigma_s a_{1x} + b_1(a_{1x} - s_x) \right] \quad (2.15)
 \end{aligned}$$

In this model, b_1 and u_s are unknown parameters.

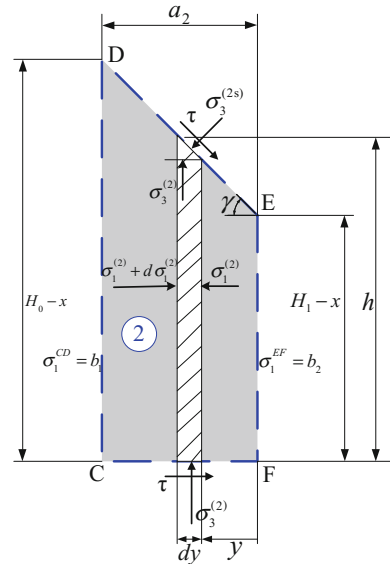
(b) Modeling of the sub-unit 2

A micro-unit with the width of dy at the sub-unit 2 is taken, as shown in Fig. 2.6. According to the force balance, the total force in the y direction can be written as follows:

$$\begin{aligned}
 \sigma_1^{(2)} h L - (\sigma_1^{(2)} + d\sigma_1^{(2)})(h + tg\gamma dy)L - \tau \frac{dy}{\cos \gamma} L \cos \gamma - \tau L dy + \sigma_3^{(2s)} \frac{dy}{\cos \gamma} L \sin \gamma &= 0 \quad (2.16)
 \end{aligned}$$

Here, h is the height of the micro-unit, and γ is the angle of the slope at sub-unit 2. The normal stresses $\sigma_1^{(2)}$ and $\sigma_3^{(2s)}$ are described in Fig. 2.6, where the superscript (2) represents the sub-unit 2.

Fig. 2.6 Stress analysis of the sub-unit 2 at the stage 1



Ignoring the higher-order term $d\sigma_1^{(2)} \cdot dy$, the above equation may be rewritten as:

$$-\sigma_1^{(2)}tg\gamma dy - d\sigma_1^{(2)}h - 2\tau dy + \sigma_3^{(2s)}tg\gamma dy = 0 \quad (2.17)$$

According to the force balance, the total force in the x direction can be written as follows:

$$\sigma_3^{(2s)} \frac{dy}{\cos \gamma} L \cos \gamma = \sigma_3^{(2)} L dy - \tau \frac{dy}{\cos \gamma} L \sin \gamma \quad (2.18)$$

Equation (2.18) may be rewritten as:

$$\sigma_3^{(2s)} = \sigma_3^{(2)} - \tau tg\gamma \quad (2.19)$$

From Eqs. (2.17) and (2.19), we have

$$-\sigma_1^{(2)}k_1 dy - hd\sigma_1^{(2)} - \tau(2 + k_1^2)dy + \sigma_3^{(2)}k_1 dy = 0 \quad (2.20)$$

Here $tg\gamma = k_1$. According to the plastic conditions of the plane problem [4, 5], the following is true:

$$\sigma_3^{(2)} - \sigma_1^{(2)} = \frac{2}{\sqrt{3}} \sigma_s \quad (2.21)$$

Equations (2.20) and (2.21) produce the following:

$$\frac{2}{\sqrt{3}} \sigma_s k_1 dy - hd\sigma_1^{(2)} - \tau dy(2 + k_1^2) = 0 \quad (2.22)$$

Here, the height h of the micro-unit can be rewritten as follows:

$$h = H_1 - x + ytg\gamma = H_1 - x + yk_1 \quad (2.23)$$

Inserting Eq. (2.22) into Eq. (2.23), we have

$$d\sigma_1^{(2)} = -\frac{k_2}{H_1 - x + yk_1} dy = -\frac{k_2}{k_1} \frac{d(H_1 - x + yk_1)}{H_1 - x + yk_1} \quad (2.24)$$

with $k_2 = -\frac{2}{\sqrt{3}} \sigma_s k_1 + \tau(2 + k_1^2)$

The integral of Eq. (2.24) gives the following:

$$\sigma_1^{(2)} = -\frac{k_2}{k_1} \ln(H_1 - x + yk) + c \quad (2.25)$$

The following boundary condition exists:

$$\left. \begin{aligned} \sigma_1^{(2)}(y = a_2) &= b_1 \\ \sigma_1^{(2)}(y = 0) &= b_2 \end{aligned} \right\} \quad (2.26)$$

The first boundary condition guarantees the model continuity between the sub-units 1 and 2. Inserting Eq. (2.25) into Eq. (2.26), we have

$$\left. \begin{aligned} b_2 &= b_1 - \frac{K_2}{K_1} \ln \frac{H_1 - x}{H_0 - x} \\ c &= b_1 + \frac{K_2}{K_1} \ln(H_0 - x) \end{aligned} \right\} \quad (2.27)$$

In this way, from (2.21), (2.25) and (2.27), the normal stress at the contact region can be rewritten as follows:

$$\sigma_3^{(2)} = \frac{K_2}{K_1} \frac{H_0 - x}{H_1 - x + yk} + b_1 + \frac{2}{\sqrt{3}} \sigma_s \quad (2.28)$$

Then, by integrating the stress of the sub-unit 2, the deformation force P_{12} of the sub-unit 2 on the contact region is easily expressed as follows:

$$\begin{aligned} P_{12} &= \int_0^{a_2} \sigma_3^{(2)} L dy = L \times \left\{ -\frac{K_2}{K_1^2} [(H_0 - x) \ln(H_0 - x) - (H_1 - x) \ln(H_1 - x) - (H_0 - H_1)] \right. \\ &\quad \left. + \left(\frac{K_2}{K_1} \ln h_0 + \frac{2}{\sqrt{3}} \sigma_s + b_1 \right) a_2 \right\} \end{aligned} \quad (2.29)$$

Similarly, according to the continuity conditions between two adjacent sub-units, the forging deformation forces P_{13} , P_{14} of the units 3, 4 at the sub-process 1 are easily derived. Thus, at the sub-process 1, the deformation force can be derived as

$$P_1 = P_{11} + P_{12} + P_{13} + P_{14} \quad (2.30)$$

Also, the deformation force of the sub-processes 2 and 3 may be obtained using the similar method.

2.2.2 Global Deformation Force Model and Modeling Performance Analysis

The deformation force model in the whole forging process may be described as follows:

$$P = \begin{cases} P_{11} + P_{12} + P_{13} + P_{14} & \text{at the sub-process 1} \\ P_{21} + P_{22} + P_{23} + P_{24} + P_{25} & \text{at the sub-process 2} \\ P_{31} + P_{32} + P_{33} + P_{34} + P_{35} + P_{36} & \text{at the sub-process 3} \end{cases} \quad (2.31)$$

where $P_{21}, P_{22}, P_{23}, P_{24}, P_{25}$ are the forging deformation forces of the sub-units 1, 2, 3, 4, 5 in the sub-process 2 respectively, and $P_{31}, P_{32}, P_{33}, P_{34}, P_{35}, P_{36}$ are the forging deformation forces of the sub-units 1, 2, 3, 4, 5, 6 in the sub-process 3.

The continuity between two adjacent sub-units in each sub-process is guaranteed by the boundary conditions during the derivation of the model. For example, the first boundary condition in Eq. (2.26) guarantees the continuity of the sub-units 1 and 2 in the sub-process 1. Then, the continuity between two adjacent sub-processes is proven. Without loss of generality, we prove the continuity between the sub-processes 1 and 2. There is a more sub-unit 5 in the sub-process 2 compared to the sub-process 1. Thus, we only need to prove the continuity at the birth of the sub-unit 5, whose condition is that the deformation force model of the sub-unit 5 at the sub-process 2 is zero and the deformation forces of other units in the sub-process 1 should keep invariable at the birth of this sub-unit 5.

Under the same calculation method of the deformation force P_{12} of the sub-unit 2 in the sub-process 1, the deformation force of the sub-unit 5 in the sub-process 2 is derived as below:

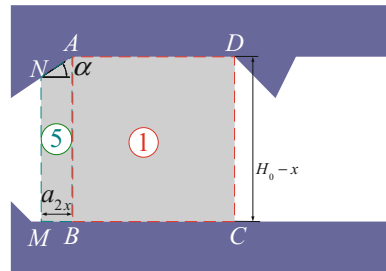
$$P_{25} = L \times \left\{ -\frac{k_4}{k_3} [(H_0 - x - k_3 a_{2x}) \ln(H_0 - x - k_3 a_{2x}) - (H_0 - x) \ln(H_0 - x) + k_3 a_{2x}] \right. \\ \left. + \left[-\frac{k_4}{k_3} \ln(H_0 - x - k_3 a_{2x}) + \frac{2}{\sqrt{3}} \sigma_s \right] a_{2x} \right\} \quad (2.32)$$

Here, $K_3 = tg\alpha$, $K_4 = \mu_s \sigma_s (2 + tg^2\alpha) + \frac{2}{\sqrt{3}} \sigma_s K_3$, a_{2x} is the real-time width of the sub-unit 5 in the sub-stage 2, other geometric parameters are shown in Fig. 2.7.

When the birth of the sub-unit 5, we have $a_{2x} = 0$. Inserting this condition into Eq. (2.32), the deformation force of the sub-unit 5 is calculated as

$$P_{25}(a_{2x} = 0) = 0 \quad (2.33)$$

Fig. 2.7 Geometric relation of the sub-unit 5 at the sub-stage 2



Moreover, at the birth of the sub-unit 5, the boundary conditions $\sigma_1^{AB} = 0$ and $\sigma_1^{CD} = b_1$ are still maintained, which guarantees that $P_{11} = P_{21}$. Similarly, deformation forces of other units also keep invariable at the birth of the sub-unit 5. Thus, the continuous condition at the birth of the sub-unit 5 is satisfied and the models between the sub-process 1 and sub-process 2 are continuous. Similarly, it may also prove the continuity between the sub-processes 2 and 3. Thus, the whole forging process model is continuous.

In the global model, many parameters are unknown, such as the boundary conditions at the sub-unit 1. They can be easily identified from the deformation process data. Since there are many studies about parameter identification, this chapter will pay no attention to this.

2.3 Model Analysis and Verification

In this section, both simulations and experiment are used to confirm the validity of the proposed modeling method.

2.3.1 Simulation Verification

The efficiency and accuracy of the model built by the proposed method will be analyzed and verified in simulation with the commercial software, Design Environment for Forming (DEFORM). The DEFORM software can simulate the entire forging process effectively. In DEFORM, a rigid-plastic finite element method is used to numerically simulate the nonlinear forging process. Its theoretical basis is the Markov variational principle and it obeys the basic equations of plasticity. It also employs the direct iterative method to solve each step and the convergence criterion is set as follows

$$\|e\| = \|V^n - V^{n-1}\| \leq 5 \times 10^{-3} \quad (2.34)$$

Here, V^n is the generable variable value of the current n th iteration.

In the DEFORM software, the friction coefficient is set equal to a constant value, which is usually a mean of all friction coefficients between the dies and the forging. It is given according to the experience of the experts or the material experiments. In the simulations of this paper, the friction coefficient is set equal to 0.2 according to the expert's experience and the experiment for lubricated hot forming processes presented in the references [24–26].

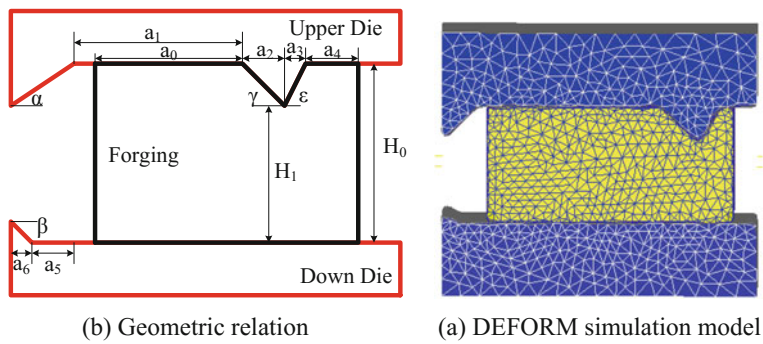


Fig. 2.8 Simulation model

(a) Case 1

Three forgings are used in this verification. In these forgings, the shape of the workpieces and the dies are shown in Fig. 2.8 and their material is the aluminum alloy (AL-1100) and the forging temperature is equal to 493.15 K. Their material model is set as the Rosserd material model (Eq. 2.8), whose parameters are set as $c = 97.971$, $m = 0.0453753$, $n = 0.450113$, $k = 31.6024$ according to the aluminum alloy (AL-1100) characteristics. The size and the forging velocity in each forging are shown in Table 2.1. One of the workpieces at the before- and after-forged are shown in Fig. 2.9a, b respectively.

Table 2.1 Forging conditions

	Geometric parameters (mm)													Velocity v (mm/s)
	a_6	a_5	a_1	α	β	γ	ε	a_0	a_2	a_3	a_4	H_0	H_1	
Forging 1	38.04	40	400	45°	30°	45°	60°	380	80	46.19	30	250	170	1
Forging 2	30	30	360	45°	30°	45°	60°	330	50	34.64	20	200	150	0.5
Forging 3	20	30	200	45°	30°	45°	60°	190	30	17.32	20	180	150	0.3

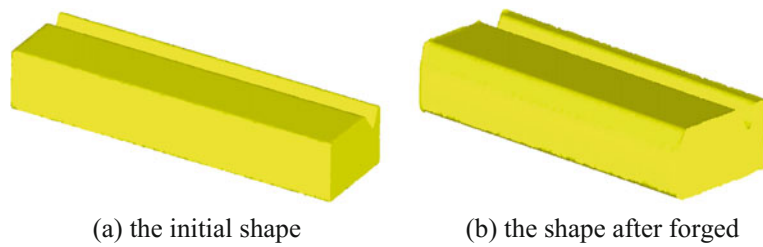


Fig. 2.9 Shapes of workpiece at before- and after-forged

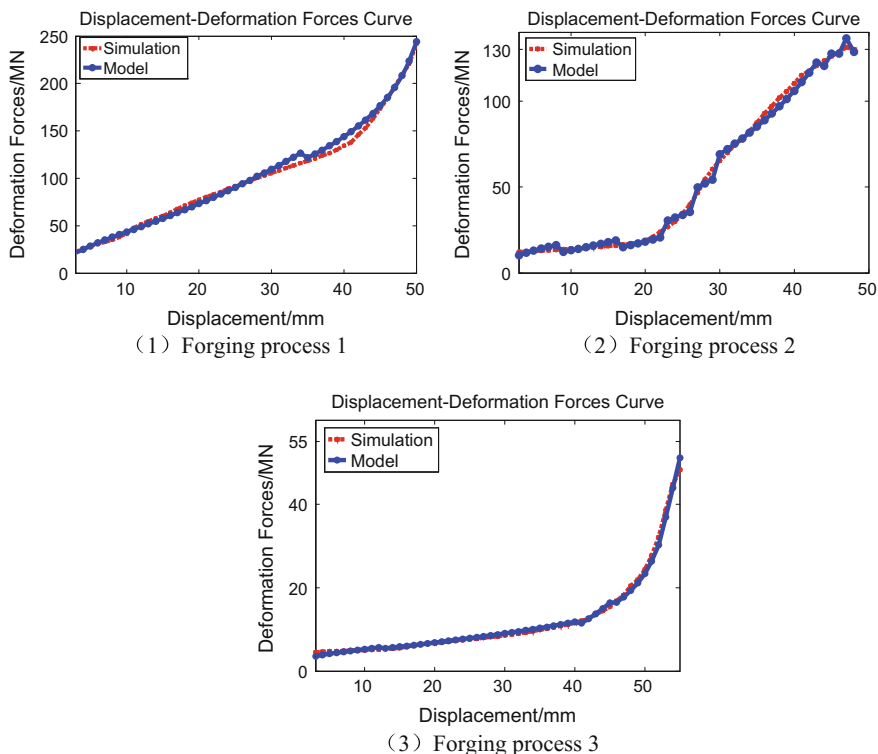


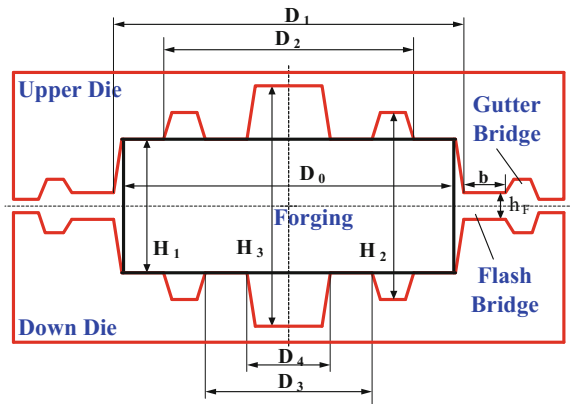
Fig. 2.10 Deformation forces from the simulation and the model (red star lines—simulation; blue circle lines—model)

In each forging simulation, the workpiece and the dies are split into the micro-units by the 60,000 grid number. The deformation forces of these forging processes in simulation are shown in Fig. 2.10 (red star lines). Then, the proposed modeling method is used to model the deformation forces of these forging processes. In the model derivation of each forging process, the material model and the geometric sizes in Table 2.1 are inserted into the model (2.31), from which the global deformation force in the whole deformation process can be derived. Unknown parameters in the global model are further identified by the deformation force data from simulation. The predictive values of this global model are demonstrated in Fig. 2.10 (see blue circle line). From Fig. 2.10, it shows that these models are closely consistent with the output as observed under the simulations. These results prove that the proposed modeling method is effective.

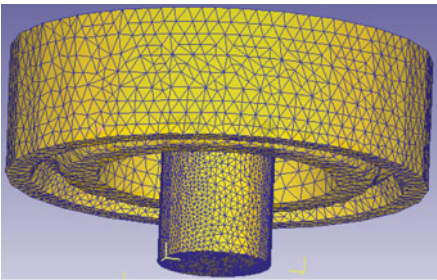
(b) Case 2

In this verification, three cylinder workpieces are forged under different velocities. Their material model is described by Eq. (2.8). The upper and down dies and the shapes of the workpieces are shown in Figs. 2.11. The size and the forging velocity

Fig. 2.11 Simulation model



(a) Geometric relation



(b) DEFORM simulation model

Table 2.2 Forging conditions

	Geometric parameters (mm)										Velocity v (mm/s)
	D_0	D_1	D_2	D_3	D_4	H_1	H_2	H_3	b	h_F	
Forging 1	400	421.96	280	200	80	250	330	410	60	60	0.5
Forging 2	320	335.66	220	140	60	180	260	300	55	50	1
Forging 3	240	253.56	160	120	40	180	220	260	50	50	0.3

in each forging are shown in Table 2.2. The workpieces at the before- and after-forged are shown in Fig. 2.12a, b respectively.

In each forging simulation, the workpiece and the dies are split into the micro-units by the 60,000 grid number. This forging process is divided into four stages as shown in Fig. 2.13. The simulation data of these forging processes are shown in Fig. 2.14 (red star lines). Then, the proposed modeling method is used to model the deformation forces of these forging processes. In the model derivation of each forging process, the material model and the geometric sizes in Table 2.2 are inserted into the model (2.31), from which the deformation force in the whole

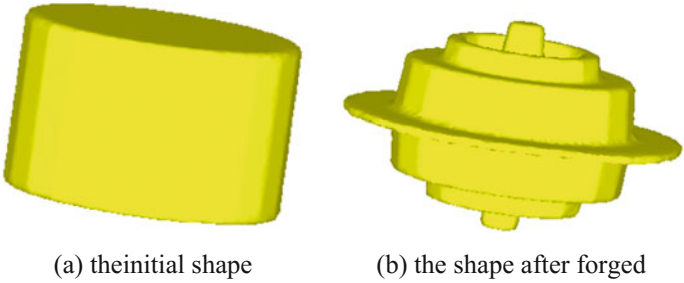


Fig. 2.12 Shapes of workpiece at before- and after-forged

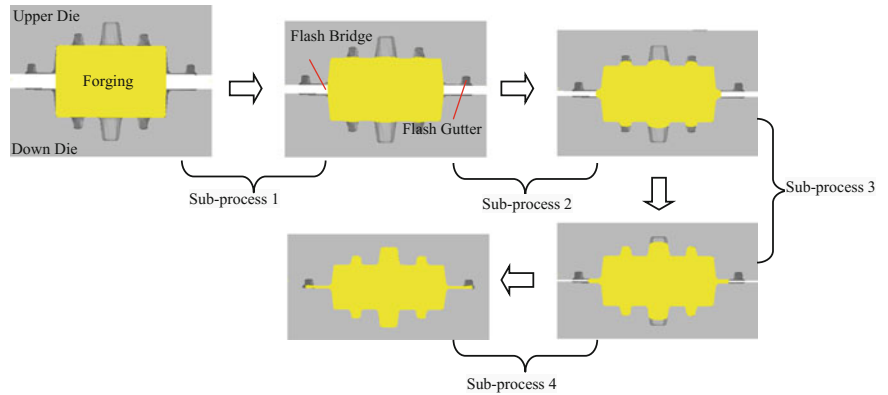


Fig. 2.13 Process decomposition

deformation process can be derived. Unknown parameters in the global model are further identified by the deformation force data from simulation. The predictive values of this global model are also demonstrated in Fig. 2.14 (see blue circle line). Figure 2.14 shows that these models are closely consistent with the output as observed under the simulations. These results also prove that the proposed modeling method is effective.

2.3.2 Experiment Verification

The experiments on the practical 4000T HPM are used to verify the effectiveness of the model. The schematic of the experimental setup is shown in Fig. 2.15. The entire system is powered by a pump station, which can produce the maximal 25 MPa oil pressure. Three driving cylinders located above the work plate are

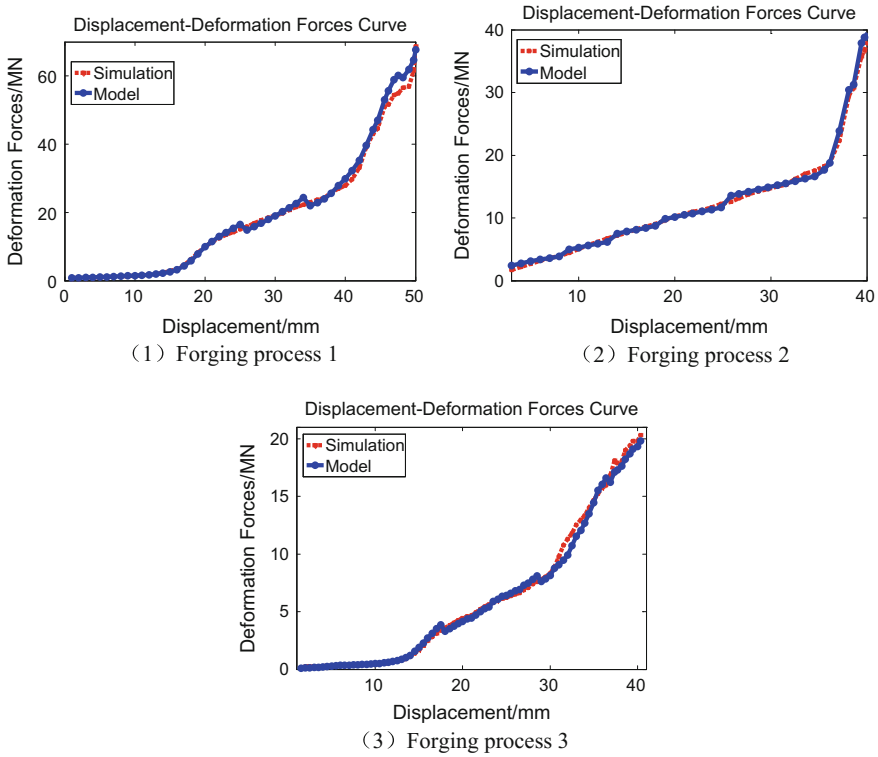


Fig. 2.14 Deformation forces from the simulation and the model (red star lines—simulation; blue circle lines—model)

controlled by a servovalve. This servovalve receives control signals from a control panel equipped with a PC, a PLC (SIMATICS7-300) and a data acquisition board for pressure, displacement and velocity measurement. The pressure data are collected using the pressure sensors installed at the inlet of the driven cylinders (E-ART-6/400, range: 0–400 bar). The displacement sensors (Magnetostrictive sensors: RPS 1650M D70 1S1 G8400, resolution: 0.001 mm) are installed at the vertical columns. The characteristic parameters of the HPM are shown in Table 2.3.

In this model verification, a complex workpiece with 7085 aluminum alloy is forged. The workpieces at the before- and after-forged are shown in Fig. 2.16a, b respectively. The details of this experiment may see the references [24, 25].

Then, this forging process is divided into three stages: the contacting stage, the upsetting stage and the reverse extrusion stage. The experimental output is shown in Fig. 2.17 (see star line). Then, the deformation force model is derived by using the proposed method. Unknown parameters in the deformation force model are further identified by using deformation force data, which are indirectly obtained via the

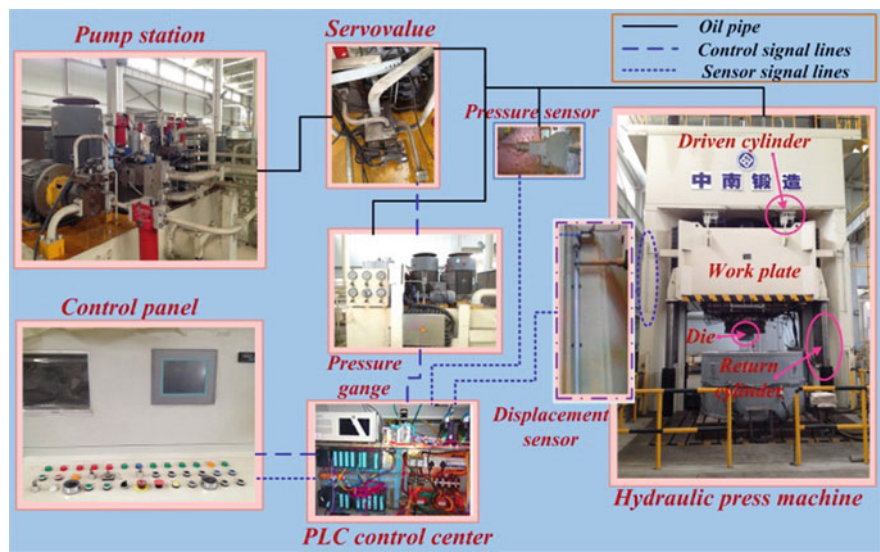


Fig. 2.15 Practical 4000T HPM

Table 2.3 System parameters

Description	Value	Description	Value
Maximal driving force	40,000 KN	Driving cylinder area	0.52 m ²
Operating stroke	1.6 m	Return cylinder area	0.038 m ²
Mass of work plate	54,474 kg	Maximal oil pressure	25 MPa

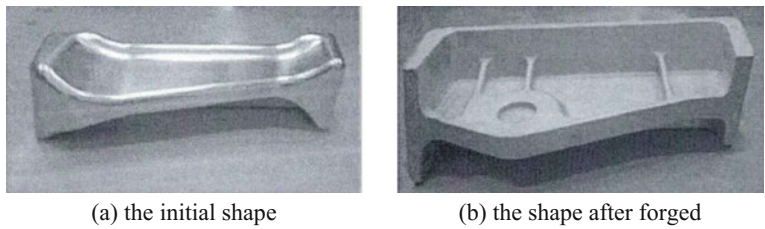
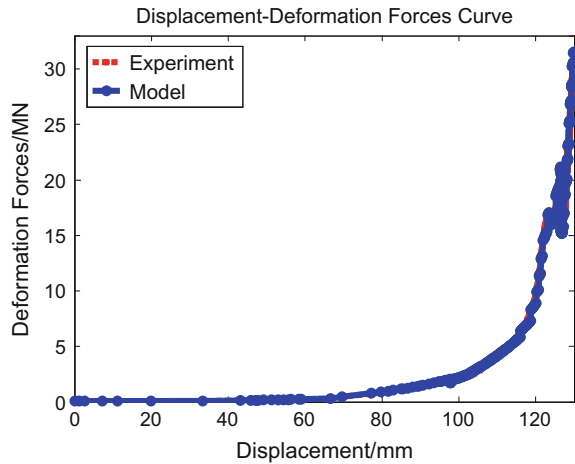


Fig. 2.16 Shapes of workpiece at before- and after-forged

motion model of the HPM. The predictive values of this model are also demonstrated in Fig. 2.17 (see circle line). From Fig. 2.17, this model is closely consistent with the output as observed under practical circumstances. This experiment further proves the effectiveness of the proposed modeling method.

Fig. 2.17 Deformation forces from the experiment and model



2.4 Conclusion

A process/shape-decomposition modeling method is proposed and tested here for the deformation force estimation in a complex forging process. The model is found capable of predicting the deformation force of the whole forging process very well. Since the proposed method decomposes the modeling complexity of the whole forging process into many simple and easily sub-modeling tasks, it can greatly reduce the complexity of the modeling process. This means that this proposed method can be applied to very complex forging processes. Unknown parameters in the model can be more easily determined by identification on the forging data. All these will benefit the real-time prediction and control of the deformation process. Experiments and simulations have confirmed the effectiveness of the proposed method.

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