Forming characteristics and mechanism of double-roll rotary forging for large-diameter and thin-walled metal discs

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Received: 12 July 2021 / Accepted: 15 January 2022 / Published online: 26 January 2022 © The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
Double-roll rotary forging is an emerging plastic forming technology based on rotary forging. Owing to the advantages of labor saving, small eccentric load, low noise and vibration, good uniformity, high surface quality, and material saving, it is very promising for fabrication of large-diameter thin-walled disc. To date, a few relevant researches on the double-roll rotary forging technology of large-diameter thin-walled metal discs have been reported, and the forming mechanisms and process of disc workpieces remain uninvestigated. Herein, a 3D rigid-plastic finite element model (FEM) is established to simulate the fabrication process of large-diameter thin-walled disc; four geometric features appear in the forming process: "mushroom" shape, "upper drum" shape, "drum shape" shape, and "lower drum" shape. Equivalent stress, equivalent strain, and temperature field of these four geometric shapes are analyzed, and the forming mechanism of these four geometric shapes is revealed. The reliability and accuracy of FEM are verified through experiments, and the four geometric shape features occur in the process are consistent with the simulation. The research results provide valuable guidelines for better understanding of double-roll rotary forging for the fabrication of large-diameter thin-walled discs.

Keywords Double-roll rotary forging · Large-diameter thin-walled disc · FEM · Geometric shape characteristics · Deformation mechanism

1 Introduction
Large-diameter and thin-walled metal discs are key components in nuclear power, aerospace, deep-sea exploration, and other industrial fields. Conventional processes for manufacturing large-diameter and thin-walled metal discs comprise hot die forging and hammer forging or isothermal forging [1–3]. With the larger diameter and thin-walled metal discs used increasingly, it leads to a significant increase in the forming load. Therefore, huge forging tonnage restricts the development of the manufacture of large-diameter and thin-walled metal discs. Hot rolling technology can enlarge near shape forming capability and reduce costs by a decrease of tooling and forging equipment costs [4–6]. However, the formed shapes of hot rolling require extensive machining to produce the final disc workpiece, this disrupts the metal flow and affects the performance of the disc workpiece. To prepare large-diameter and thin-walled metal discs with better performance, rotary forging technology has been introduced due to the advantage of labor-saving, low noise and vibration, good uniformity, materials saving, and metal streamline integrity.

Till now, many scholars have studied the rotary forging process, the early researches mainly concentrated on the distribution of energy and load [7, 8], metal flow [9, 10], and forming defects [11–13], which established the fundamental laws for the workpiece forming. However, the forming characteristics and mechanism of rotary forging were not studied in depth until the rise of finite element methods. G. Liu and Shijian Yuan [14–16] first used a 3D rigid-plastic finite element model to study the forming mechanism of discs and pins, but elastic deformation of the workpiece was not considered. Based on G. Liu’s study, Xinghui Han and Lin Hua [17–21] established a 3D elastoplastic finite element model to study the forming characteristics of discs and rings; to further improve the accuracy of the 3D elastoplastic finite element model, they revised the friction coefficient [22] and studied the contact pressure,
slip distance, and mold wear [23–26], which significantly promote the reliability of FEM for forging application. Apart from these studies that focus on the cold rotary forging process, Yong Zheng [27–30] studied the hot rotary forging by investigating the forming characteristics of flanges and discs, which is more favorable for less deformable materials.

The above researches associate with the rotary forging process take advantage of a single roll, and the contact area between the upper die and the workpiece is located on one side of the workpiece; thus, eccentric load will appear during the forming process. As the size of the workpiece grows, the eccentric load will become more significant, which is detrimental for the large-size workpiece forging process. In addition, when the workpiece is very thin, it will warp easily on the side that is not rolled. Therefore, rotary forging technology is unavailable to form large-diameter thin-walled disc workpieces. To address this problem, we [31] proposed for the first time a double-roll rotary forging method and designed the double-roll forging machine, which transformed a single roll into two symmetrical rolls along the central axis of the two main shafts. This technology remarkably reduced the influence of the eccentric load of the workpiece during the forming process and improved the forming size limit of the rotary forging process, making the forming process more stable. To date, relevant FEM models and experiments have not been reported.

Herein, this work studies the forming characteristics and mechanism of the large-diameter thin-walled metal disc by double-roll rotary forging. A 3D rigid-plastic finite element model (FEM) was established first to simulate the fabrication process of the large-diameter thin-walled disc; four geometric features appeared in the forming process: “mushroom” shape, “upper drum” shape, “drum shape” shape, and “lower drum” shape. The characteristic of equivalent stress, equivalent strain, and temperature field of these four geometric shapes were studied in detail, and the forming mechanism of these four geometric shapes was illustrated accordingly. The reliability and accuracy of FEM are further verified through experiments and the four geometric shape features that occurred in the forging process, which are consistent with the FEM simulations process. The research results provide valuable guidelines for a better understanding of double-roll rotary forging and offered a promising technology for the fabrication of large-diameter thin-walled discs and provide ideas for us to prepare special-shaped parts.

2 3D FE modeling of double-roll rotary forging

2.1 Working principle of double-roll rotary forging

The working principle of double-roll rotary forging integral forming of large-diameter thin-walled metal disc is shown in Fig. 1: The double rollers continuously rotate around the central axis of the main shaft of the equipment, and the lower die feeds the disc workpiece upwards simultaneously. When the disc workpiece is in contact with the double rollers, the double rollers rotate around their spinning axis under the actuation of friction force between the disc workpiece and the rollers to realize the integral forming of the large-diameter thin-walled metal disc. As soon as the disc workpiece is formed to the target height, the lower die stops feeding upwards while the double rollers continue to rotate to flatten the upper surface of the disc workpiece.

2.2 3D FE model and boundary conditions

The characteristics of highly nonlinear, local contact, large plastic deformation, and complex dynamic plastic flow process from the axial, radial, and circumferential exist during hot double-roll rotary forging, to better reveal the plastic deformation mechanism and stress, strain, and other characteristics of the workpiece. Therefore, 3D-DEFORM software is selected to establish the finite element model of the integral forming of the large-diameter thin-walled metal disc double-roller rotary forging. As shown in Fig. 2, both the upper die and the lower die are set as a rigid body, and the material of the workpiece is AISI-1020, and it is set as a plastic body. The stress–strain relationship of AISI-1020 comes from the material library in Deform-3D software, as shown in Fig. 3. The mechanical properties of AISI1020 material are shown in Table 1. The friction coefficient and thermal conductivity between the die and workpiece selected in these literature are 0.3 and 11 (N/s·mm·°C), respectively [32, 33], whereas the friction between the upper die and the workpiece is rolling friction, so we choose the friction coefficient of the upper die and workpiece to be 0.1, as shown in Table 2. The contact pressure between the die and the workpiece will continue to increase during the forming process, which will increase the thermal conductivity coefficient between the die and the workpiece. Therefore, we choose the thermal conductivity coefficient between the die and the workpiece to be 15 (N/s·mm·°C), as shown in Table 2.

Due to the gap between the upper die of the double-roll rotary forging equipment, as shown in Fig. 2, the metal flow in this area is complicated, and the grid is distorted seriously. To reduce the distortion of elements, the local mesh technology is employed with the mesh area refined by 100 times. Other parameters in the finite element simulation process are shown in Table 2.

2.3 Determination of die movement relationship

The movement curve of the large-diameter thin-walled metal disc double-cone roller rotating forging is shown in Fig. 4.
The selection of the motion relationship is shown in Fig. 1. During the forming process of the workpiece, the equation of the contact surface AC between the upper die and the upper surface of the workpiece in the Cartesian coordinate system is as follows:

\[ y = \sqrt{2S \frac{2x}{S} + 1} \]  

In the formula, \( S \) is the downward pressure per revolution of the upper die, and the unit is mm/r.

Assuming that the outer edge of the disc workpiece is still circular during the forming process, the edges of the workpiece satisfy the following equation:

\[ x^2 + y^2 = R^2 \]  

where \( R \) is the radius of the outer edge of the disc workpiece.

In Fig. 1, \( \angle BAC = \theta \); according to Eqs. (1) and (2), the value of \( \theta \) is obtained:

\[ \theta = \arccos \left( 1 - \frac{\sqrt{2S}}{R} \right) \]
As \( S = 60v/n \):

\[
\theta = \arccos \left( 1 - \frac{60 \times 2^v}{nR} \right) \quad (4)
\]

where \( n \) is the rotation speed of the upper die (rad/s), and \( v \) is the feed speed of the lower die (mm/s).

During the forming process of the workpiece, the contact area between the upper die and the workpiece is a space spiral surface, so the upper die is not completely in contact with the upper surface of the workpiece. Therefore, the value range is shown in formula (5):

\[ 0 \leq \theta < \pi \quad (5) \]

From Eqs. (4) and (5), it can be obtained that:

\[ 0 \leq \frac{30 \times \sqrt{2^v}}{n} < R \quad (6) \]

Therefore, in the forming process of the workpiece, formula (6) needs to be satisfied among the rotation speed \( n \) of the upper die, the feed speed \( v \) of the lower die, and the radius \( R \) of the workpiece. A reasonable movement relationship can be selected according to formula (6). At the same time, when the workpiece is formed to the target height, the upper die continues to rotate until the upper surface of the workpiece is rolled into a flat surface.

3 Results and discussion

3.1 Description and definition of geometric features

To study the forming process, the characteristic geometric features at different stages of the workpiece are studied, as shown in Fig. 5. Figure 5 a is the initial shape feature of the workpiece, which is a standard cylindrical part. As the process progress, the “mushroom” shape will appear with the outer diameter of the workpiece decreases from the upper surface to the lower surface [15]. With the increase of the deformation, another characteristic geometric shape occurs where the maximum outer diameter of the workpiece is in the upper half of the workpiece.

| Table 1 | Mechanical and thermal properties of disc workpieces |
| Simulations parameters | AISI1020 |
|-------------------------|---------|
| Density, \( \rho \) (kg/m\(^3\)) | 7800 |
| Young’s modulus (GPa) | 210 |
| Poisson’s ratio (\( \mu \)) | 0.3 |
| Thermal conductivity (J/(m·s·K)) | 24.5 |
| Specific heat capacity (J/(kg·K)) | 7.2 |
| Thermal expansion coefficient (1/K) | \( 13.16 \times 10^{-6} \) |
| Constitutive equation | \( \sigma = \hat{\sigma}(T, \dot{T}, T) \) |

| Table 2 | Parameters in the finite element simulation process |
| Parameters | Value |
|-------------------------|---------|
| The initial diameter of workpiece, \( D_0 \) (mm) | 244 |
| The initial height of workpiece, \( H_0 \) (mm) | 35 |
| The initial temperature of the workpiece (\( ^\circ \text{C} \)) | 1100 |
| The initial temperature of upper die, \( T \) (\( ^\circ \text{C} \)) | 20 |
| Coefficient of friction between upper die and workpiece | 0.1 |
| Coefficient of friction between lower die and workpiece | 0.7 |
| Thermal conductivity between die and workpiece (N/s-mm\(^°\text{C}^{-1}\)) | 15 |
According to its geometric shape, we define it as an “upper drum” shape. Then, the maximum outer diameter of the workpiece drops to the middle height of the workpiece as the process goes on (Fig. 5d); we define this shape as a “drum” shape. The final characteristic geometric shape is shown in Fig. 5e, the maximum outer diameter of the workpiece is in the lower half of the workpiece, and we define it as a “lower drum” shape. The four featured geometric shapes above emerged gradually as the result of the increased deformation of the workpiece.

Fig. 4 Motion curve formed by double-roll rotary forging of a large-diameter thin-walled metal disc

Fig. 5 Geometry characteristics at different forming stages of the workpiece. a $t=0$ s, “cylindrical” shape; b $t=3.2$ s, “mushroom” shape; c $t=7.0$ s, “upper drum” shape; d $t=10.2$ s, “drum” shape; e $t=13.2$ s, “lower drum” shape
Therefore, the forming process of the workpiece can be divided into four stages according to the change of the geometric characteristics of the workpiece. The first is the "mushroom"-shaped stage, the second is the "upper drum"-shaped stage, the third is the "drum" stage, and the last is the "lower drum"-shaped stage. The features and mechanisms of these four geometric shapes will be elaborated in detail below.

### 3.2 “Mushroom” shape characteristics and mechanism

In the "mushroom" stage, the upper die is in partial contact with the workpiece, the stress is mainly located in the contact area, and the equivalent stress distribution characteristics are shown in Fig. 6a. As the upper die and the workpiece are in partial contact, the contact area of the upper die and the workpiece is smaller than that between the lower die and the workpiece. Therefore, the average axial compressive stress on the upper surface of the workpiece is greater than the lower surface of the workpiece [21]. Since the stress wave is gradually transferred from the upper surface of the workpiece to the lower surface of the workpiece, the equivalent plastic strain zone will gradually drop from the upper surface of the workpiece to the lower surface of the workpiece. Similar to rotary forging, the upper die of double-roll rotary forging also rotates in the circumferential direction, so the equivalent plastic strain distribution of the disc workpiece is very uniform in the circumferential direction. At the same time, due to the gap between the two symmetrical double rollers of the upper die, the metal in this area cannot be crushed by the upper die, the equivalent plastic strain at the center of the disc workpiece is very small, and the equivalent plastic strain is symmetrical along the center of the disc in the radial direction. The distribution characteristics of the equivalent plastic strain of the disc workpiece along with the axial, radial, and circumferential directions at this stage are shown in Fig. 6b. In the initial stage, the temperature of the die is relatively low, heat conduction is dominant as a result of the huge temperature difference, so the heat conduction between the die and the workpiece will reduce the temperature of the surface of the disc workpiece; however, due to the limited contact time between the die and the workpiece and the heat generation from the friction between the upper die and the workpiece, the disc workpiece has little heat loss. Therefore, the temperature of the disc workpiece is high at this stage, and its temperature distribution characteristics are shown in Fig. 6c.

To study the forming mechanism of the “mushroom” feature in detail, point tracking technology is applied, and 300 points are uniformly selected on the upper surface line segment A1B1, lower surface line segment C1D1, the middle part line segment E1F1 of the workpiece respectively, as shown in Fig. 6d. The resulting equivalent plastic strain distribution along the radial direction in different height directions is shown in Fig. 6e. In addition, we selected four discontinuous total strain values to make the total strain distribution more intuitive, as shown in Fig. 6f. The equivalent plastic strain on the upper surface of the workpiece has a maximum value at a distance of about 1/5R from the center of the circle. From the radial position of the maximum equivalent strain to the center of the disc, the equivalent plastic deformation decreases sharply, and the equivalent plastic strain also decreases gradually toward the outer edge of the disc. This is determined by the distribution characteristics of the rolling force of the upper die on the disc workpiece and the gap between the die on the center area of the disc [8]. The equivalent plastic strain in the middle and lower regions of the disc workpiece is very small; this is owing to that the equivalent plastic strain only occurs on the upper part of the workpiece and has not been transmitted to the middle region of the workpiece. At this stage, the metal fluidity of the upper surface of the disc workpiece is better; its radial equivalent plastic strain distribution and the outer metal flow direction are shown in Fig. 6f. Due to the high temperature of the entire disc workpiece, the metal on the upper surface of the disc workpiece flows faster in the radial direction; therefore, the geometric features of the workpiece will change from a “cylindrical” shape to a “mushroom” shape.

The above analysis demonstrates that the equivalent plastic strain of the disc workpiece from the upper surface to the lower surface is uneven at this stage. The geometric shape is featured as a “mushroom” shape, which is similar to a defect in the process of forming a thin-walled disc workpiece. However, this phenomenon can be used to manufacture thin-walled flanges. Therefore, the “mushroom” effect in double-roll rotary forging can be regarded as a special advantage of rotary forging for flanges manufacturing.

### 3.3 “Upper drum” shape characteristics and mechanism

When the disc workpiece is formed to 7.0 s, the geometric shape of the disc workpiece is “upper drum” shape. In the “upper drum” stage, the upper die is in partial contact with the workpiece, the stress is mainly located in the contact area, and the equivalent stress distribution characteristics are shown in Fig. 7a. At this stage, the upper surface of the disc workpiece enters plastic deformation except for the central area of the disc. The equivalent plastic strain is uniformly distributed along the circumferential direction, symmetrical along the center of the disc in the radial direction, and the degree of equivalent deformation gradually decreases in the axial direction from the upper surface to the lower surface of the disc. The distribution characteristics of its equivalent plasticity in the axial, radial, and circumferential directions
are shown in Fig. 7b. At this stage, the heat conduction between the die and the disc workpiece will reduce the temperature of the workpiece surface due to enough contacting time and a huge temperature difference despite the friction between the upper die and the workpiece. Nevertheless, the heat conduction has not reached the inside of the workpiece. Therefore, the surface temperature of the workpiece is comparatively low, and the internal metal temperature is still high; its temperature distribution characteristics are shown in Fig. 7c.

To study the forming mechanism of the “upper drum” feature in detail, point tracking technology is applied, with 300 points uniformly selected on the upper surface line segment $A_2B_2$, the lower surface line segment $C_2D_2$, the middle line segment $E_2F_3$, and the line segment MN at the maximum outer diameter of the workpiece, as shown in Fig. 7d. The resulting equivalent plastic strain distribution along the radial direction in different height directions is shown in Fig. 7e. The metal in the upper region has the highest equivalent plastic strain degree, and the metals in the middle region have all entered a state of plastic deformation, but the equivalent plastic strain degree on the lower surface is close to 0. This is because that the plastic deformation zone is transferred from the upper surface of the workpiece to the middle region of the workpiece, thus exhibiting the equivalent strain distribution characteristics shown in Fig. 7e. Due to the loading characteristics of the upper die \[21\], the force of the workpiece is mainly concentrated in the outer area of the workpiece. In the axial direction of the workpiece, more metal enters the plastic deformation state in the area near the outer side of the disc. In addition, the surface of the disc workpiece is subject to the frictional resistance of the die, making it more difficult for the metal on the surface of the disc workpiece to flow in the radial direction.
Simultaneously, the metal temperature in the middle of the workpiece is higher, and the metal flows more easily. According to the law of metal flow, the outer metal in the middle area of the disc workpiece is easier to flow along the direction of diameter expansion and height reduction. The flow characteristics and the distribution characteristics of the equivalent strain distribution of the disc workpiece along the radial direction are shown in Fig. 7f; the geometric features of the workpiece change from the “mushroom” shape (Fig. 6f) to the “upper drum” shape.

### 3.4 “Drum” shape characteristics and mechanism

When the disc workpiece is formed to 10.2 s, the geometric shape of the disc workpiece is a “drum” shape. The equivalent stress distribution characteristics are shown in Fig. 8a. At this stage, the middle area and the lower surface of the workpiece near the outside of the disc have completely entered the plastic deformation state. The equivalent plastic strain is uniformly distributed along the circumferential direction, symmetrical along the center of the disc in the radial direction, and the degree of equivalent deformation gradually decreases from the upper surface to the lower surface of the disc workpiece in the axial direction. The distribution characteristics of its equivalent plasticity in the axial, radial, and circumferential directions are shown in Fig. 8b. At this stage, the temperature of the surface of the disc workpiece is reduced as the result of the dominant heat conduction between the die and the workpiece, despite the friction between the upper die and the workpiece. However, the heat conduction has not fully penetrated the inside metal of the workpiece; part of the interior metal remains high temperature. Specifically, due to severe friction and heat generation in some areas of the workpiece, the temperature of the upper
area in the middle region of the workpiece is higher than that of the lower area of the workpiece. As a consequence, the internal temperature of the workpiece is the highest, and the temperature in the upper region is higher than the temperature in the lower region. The temperature distribution characteristics of the disc workpiece in the axial, radial, and circumferential directions are shown in Fig. 8c.

To study the forming mechanism of the “drum” feature, point tracking technology is applied, with 300 points uniformly selected on the upper surface line segment $A_3B_3$, the lower surface line segment $C_3D_3$, and the middle part line segment $E_3F_3$ of the workpiece, as shown in Fig. 8d. The resulting equivalent plastic strain distribution along the radial direction in different height directions is shown in Fig. 8e. The lower surface of the workpiece undergoes minor plastic deformation because the equivalent plastic strain has been transferred to the lower surface of the workpiece at this stage, but the degree of strain is still small. At the same time, the core area of the disc workpiece begins to enter into the plastic deformation state, which is caused by the tensile stress of the surrounding metal on the metal in the core area. Due to the loading characteristics of the upper die [21], the metal in the outer area of the disc workpiece has a greater degree of plastic deformation. As the temperature in the middle area of the disc, the workpiece is high, and the surface of the workpiece is subject to the frictional resistance of the die; the metal in the outer area of the disc workpiece is easier to flow in the direction of increasing diameter and decreasing height. Therefore, the geometry of the workpiece is transformed from the “upper drum” shape to the “drum” shape.

Fig. 8 $t=10.2$ s: the “drum” shape feature and mechanism diagram of the disc workpiece. a Equivalent stress distribution diagram of disc workpiece. b The equivalent plastic strain distribution diagram of the disc workpiece. c The temperature distribution diagram of the disc workpiece. d Point tracking selection of the feature point map. e Distribution diagram of equivalent plastic strain in different height directions. f The equivalent plastic strain distribution diagram of the disc workpiece in the radial direction.
3.5 “Lower drum” shape characteristics and mechanism

When the disc workpiece is formed to 13.2 s, the geometric shape of the disc workpiece is characterized by the “lower drum” shape. The equivalent stress distribution characteristics are shown in Fig. 9a. At this stage, the disc workpieces have entered a plastic deformation state; the equivalent plastic strain is uniformly distributed along the circumferential direction and symmetrical along the center of the disc in the radial direction. In the axial direction, the degree of equivalent deformation of the disc workpiece gradually decreases from the upper surface to the lower surface. The equivalent plastic distribution characteristics are shown in Fig. 9b. At this stage, the friction between the upper die and the workpiece increases the temperature of the upper surface of the workpiece, especially the central area suffers intensive friction, which makes the temperature in the core area of the disc workpiece the highest. Meanwhile, the temperature of the metal inside the workpiece begins to decrease due to heat conduction, but the temperature in the upper area is higher than the temperature in the lower area. The temperature distribution characteristics are shown in Fig. 9c.

To study the forming mechanism of the “lower drum” feature in detail, point tracking technology is applied, and 300 points are uniformly selected on the upper surface line segment A4B4, the lower surface line segment C4D4, the middle line segment E4F4, and the line segment HI at the maximum outer diameter of the workpiece, as shown in Fig. 8d. The resulting equivalent plastic strain distribution along the radial direction in different height directions is shown in Fig. 9e. The lower surface of the disc workpiece has a

![Fig. 9](image-url)
Fig. 10  a Double-roller rotary forging equipment. b Workpiece experiment and finite element simulation process. c Physical photos of the workpiece temperature measurement, \( t = 10 \text{ s} \). d Schematic diagram of the workpiece after forming.
uniform equivalent plastic deformation. This is because the plastic deformation zone has been transferred to the lower surface of the workpiece at this stage, and uniform plastic deformation has occurred. Due to the loading characteristics of the upper die [21], in the axial direction, the degree of plastic deformation of the metal near the outer side of the disc workpiece is greater. At the same time, the temperature of the upper part of the disc workpiece is higher than the temperature of the lower part, and the surface of the workpiece is subject to the frictional resistance of the die, which makes the metal in the outer area of the disc workpiece easier to flow in the direction of increasing diameter and decreasing height. The equivalent plastic distribution of the disc workpiece in the radial direction and the outer metal flow direction at this stage are shown in Fig. 9f; the geometric shape of the workpiece is transformed from the “drum” shape (Fig. 8f) to the “lower drum” shape.

From the above analysis, it can be concluded that only when the geometric shape feature of the workpiece is transformed into a “lower drum” shape feature that all areas of the workpiece can be forged through. Therefore, to obtain a thin-walled disc workpiece with better structure and performance, it is necessary to make the deformation of the machining process not less than the deformation of the “lower drum”--shaped feature.

4 Verification experiment

The forming characteristics of the workpiece and the reliability of the finite element simulation were verified by experiments. The experiment was conducted at Wuhan University of Technology, Hubei, China. Figure 10a shows the double-roll rotary forging equipment. The process parameters during the experiment are consistent with the finite element simulation parameters, as shown in Table 2. Figure 10b is the experiment and finite element simulation of different geometric characteristics in the forming process of the disc workpiece. Figure 10c is the physical photos of the workpiece temperature measurement, \( t = 10 \) s. The instrument used is Benetech-GM1651. It can be seen that the shape of “mushroom,” “upper drum,” “drum,” and “lower drum” will appear in sequence during the forming process of disc workpieces. The experimental process is consistent with the workpiece size and temperature distribution of the finite element simulation process, which supports the reliability of the forming stage and the finite element simulation results and analysis. Figure 10d is a photo of the disc workpiece after forming; the diameter of the disc is 405 mm, and its height is 8 mm. Our experiment and the formed disc workpiece of good quality demonstrate that the double-roll rotary forging technology is very suitable for manufacturing of large-diameter thin-walled metal discs.

5 Conclusion

This paper establishes a reliable finite element model for the double-roll rotary forging of large-diameter and thin-walled metal discs. The forming characteristics of disc workpieces are studied, and the forming mechanism of four geometric features is found and revealed. Moreover, the reliability of the finite element model and analysis process was verified through experiments. The main research conclusions are as follows:

1. During the forming process of the disc workpiece, the geometrical shape of the disc workpiece will sequentially appear in “mushroom” shape, “upper drum” shape, “drum” shape, and “lower drum” shape.
2. At the beginning of the forming process, the metal on the upper surface of the disc workpiece enters the plastic deformation state first and the workpiece began to show “mushroom” geometry features. Then, the middle area of the disc workpiece enters the plastic deformation state, and the surface of the workpiece is subject to the frictional resistance of the die, making the metal on the surface of the workpiece more difficult to flow in the radial direction. Thus, the geometry shape of the workpiece will change from a “mushroom” shape to an “upper drum” shape. And then, the lower surface of the disc workpiece enters the plastic deformation state; the temperature in the upper region is higher than that in the lower region, which makes the metal in the outer region of the workpiece easier to flow in the direction of increasing diameter and decreasing height. As a result, the geometry shape of the workpiece changes from the “upper drum” shape to the “drum” shape. At last, the disc workpieces all enter a plastic deformation state, and the deformation characteristics are similar to the “drum” shape. As a consequence, the geometric shape of the workpiece changes from the “drum” shape to the “lower drum” shape.
3. These research results provide valuable guidelines for a better understanding of double-roll rotary forging for the fabrication of large-diameter thin-walled disc and provide ideas for us to prepare special-shaped parts.

Author contribution Zhongquan Yu and Chundong Zhu proposed the idea and performed the theoretical work. Zhongquan Yu and Chundong Zhu completed the writing of the paper. Zhongquan Yu, Mingchao Chen, and Site Luo performed the experimental work.

Funding The National Natural Science Foundation of China (No. 51875427) provided the support to this research.

Availability of data and material The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.
Code availability  All software used in this article is licensed.

Declarations

Ethics approval  Not applicable.

Consent to participate We would like to declare that the work described has not been published previously and not under consideration for publication elsewhere, in whole or in part.

Consent for publication All the authors listed have approved the manuscript that is enclosed.

Competing interests The authors declare no competing interests.

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