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ORIGINAL ARTICLE

Shape-property synergistic control in closed die forging of large-diameter copper alloy valve body

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Abstract
The parameters of the forging process play a crucial role in determining the appearance quality and macro/micro properties of parts. This study focuses on closed die forging of large-diameter copper alloy valve bodies, where finite element (FE) simulation and experimentation are combined to demonstrate that both workpiece cross-section and punch action sequence significantly impact forming processes and their results. By setting reasonable forging process parameters, including die temperature, workpiece temperature, a cross-section of the workpiece, punch speed, punch action sequence, and so on, forming defects, can be avoided, macroscopic mechanical properties of products can be enhanced, and the microstructure of materials can be improved. Forging process parameters include speed, temperature, and pressing force, which in turn affect stress, strain, strain rate, and temperature distributions as well as the appearance quality and macro/micro properties of the valve body. Therefore, the rational setting of process parameters can achieve the purpose of shape-property synergistic control (SPSC).

Keywords Shape-property synergistic control · Closed die forging · Finite element simulation · Copper alloy · Valve body

1 Introduction

Limited by the force energy of the forming equipment, a large-diameter forged copper alloy valve refers to a copper alloy valve with a nominal diameter greater than 50 mm that is formed through integral forging. This type of valve serves as a core basic component in various industries such as construction, chemical engineering, and shipbuilding [1, 2]. Due to the intricate shape and thin walls, the valve body is a crucial and challenging aspect of forming large-diameter valves. The conventional processing technique for large-diameter valve bodies involves casting, where the valve body blank is initially formed through sand casting before excess material is removed via machining cutting to achieve the final shape and size of the valve body. In sand casting, manufacturing defects such as those arising from copper alloy's thin wall thickness are common. If the casting speed is too fast, there is not enough time for gas to escape from the molten alloy before condensation that may result in porosity. During cooling and solidification, if liquid shrinkage and solidification shrinkage are not compensated for, voids will form at the final solidification site of the casting. Large and concentrated voids are known as shrinkage cavities, while small and scattered ones are referred to as pores. The presence of shrinkage cavities and porosity can decrease the effective bearing cross-sectional area of cast parts, leading to stress concentration and a decline in valve mechanical properties. Defects on the machined mating surface of valves can reduce air tightness and even cause leakage.

With the optimization of alloy materials and the development of forging equipment, the forming process for large-diameter valve bodies has gradually replaced casting with forging. Compared to cast valve bodies, forged ones not only boast high production efficiency and less cutting amount but also exhibit significant advantages in dimensional accuracy, microstructure, and mechanical properties. In the early stage of forging, free forging or open die forging was mainly

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used for large-diameter valve body. Gao [3] introduced the integral open die forging process of the steel power station valve body and put forward the matters for attention in the production of workpiece, heating, and pressing. Hu et al. [4] proposed a new method combining free forging with die forging to manufacture valve bodies. This method can make full use of small tonnage equipment and overcome the shortcoming of cast valve body performance. Although it has made great progress compared with casting, there are still problems such as low material utilization, easy-to-produce forging cracks, and many post-processing and finishing procedures. Zhang [5] discussed the forging performance and processing characteristics of a 250 mm diameter stainless-steel valve body. However, the forging process only shapes the outline of the valve body; however, the forging process only shapes the outline of the valve body, while turning, boring, and milling are required for its inner hole and sealing surface. Jing et al. [6] presented a general forging process and die design method for valve bodies used in oil and gas applications and analyzed reasons for poor surface quality and difficulty of die filling.

With the advent of multicored forging press and the widespread use of finite element (FE) simulation, there has been a qualitative improvement in valve body forging. Ordinary presses can only forge the external outline of the valve body, while the inner hole must be turned or milled separately. However, a multicored forging press can simultaneously form both the external outline and internal hole profile with high precision. The forging process that was previously difficult to understand can be directly displayed by finite element simulation, making the process parameters and die design more reliable and easier to optimize. Gontarz [7] presented the forming process of drop forging of a valve on a three-slide forging press, and a comparison of the two variants was made by FE simulation and experimental. The first variant is based on forming with a vertical slide at the beginning, and later with a horizontal slide. In the second variant, at the beginning the horizontal slides move, and later a vertical one. The results showed that even if the same mold was used, the different process parameters would have a significant impact on the distribution of strain and the stress state index k. Stress state index k is the ratio of the mean stress σ_m to the equivalent stress according to Huber–Mises–Hencky hypothesis σ_{HMH}, which value is between -1 and $+1$. During the forming process, the k value of the parts varies from place to place. The smaller the absolute value of k is, the more technological safety of the process can be better maintained in terms of a loss of the deformed material coherence. Inspired by this, Yin et al. [8] conducted FE simulation and experimental research on the closed die forging process of the copper alloy valve body with a nominal diameter of 25 mm. The results show that reasonable process parameters can not only effectively avoid forming defects and improve the valve body quality, but also avoid abnormal failure of the mold and prolong the life of the mold.

In the research process combined with industrial production, Yin gradually proposed the concept of shape-property synergistic control (SPSC), that is, by studying the macroscopic and microscopic coupling effects of materials in a certain forming process, the complex interaction relationship between the evolution law of microstructure and the parameters of forming process can be better understood. The purpose of SPSC is to achieve multi-objective optimization of macroscopic geometric size and microstructure properties. For the forging of the copper alloy valve body, the copper alloy has directional large deformation flow through the relative motion of the die at high temperature. The forming process parameters will not only affect the geometric accuracy of the valve body, but also affect the metal flow lines, and even affect the result of the material recrystallization. This paper will take the closed die forging of CuZn39Pb2 valve body with a nominal diameter of 50 mm as an example to study the feasibility SPSC method. The forging process parameters of the copper alloy valve body include die temperature, workpiece temperature, a cross-section of the workpiece, punch speed, and punch action sequence. Usually, the die temperature is determined by the die material and is kept within a reasonable range under the guidance of production experience. The workpiece temperature and the punch speed are reflected in the forging temperature and strain rate distribution of the material. Yin et al. [9] studied the flow behavior of CuZn39Pb2 under the hot working conditions by processing maps, and the optimal forging temperature and strain rate are determined. Therefore, this paper will focus on the influences of the shape and size of the workpiece as well as the action sequences of the punches on the SPSC.

The forged CuZn39Pb2 valve body with a nominal diameter of 50 mm is shown in Fig. 1. The valve body is used for gate valves with a standard pressure of 1.6 MPa. The forming difficulties of the forged valve body are:

(1) The nominal diameter of the valve body is large, so a large multicored forging press is needed to meet the requirements of the force energy.
(2) The shape of the central valve hole is complex and deep, and the minimum wall thickness is only 2.2 mm, resulting in a longer stroke of the central punch, which requires a higher punch strength.
(3) The ratio of the valve body height to the central valve hole diameter is 1.463. A larger aspect ratio means more resistance to the lateral flow of the metal.
(4) There is a small reinforcing rib at the bottom of the valve body, which is difficult to form.

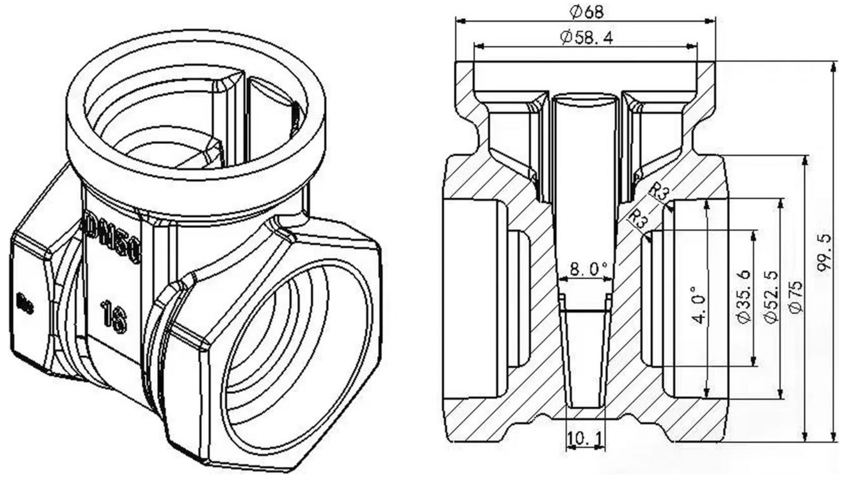

Fig. 1 Shape and dimensions of forged copper alloy valve body

In this paper, the equipment advantages of the multicore forging press and the advantages of FE simulation will be utilized to precisely form the large-diameter copper alloy valve bodies through a closed die forging process while ensuring their macro/micro properties. This research holds significant theoretical implications and market value.

2 Material and modeling of FE simulation

In this study, the Deform-3D software was utilized to simulate the closed die forging process of a copper alloy valve body made by CuZn39Pb2, whose constitutive model for flow behavior under hot working conditions is described in Yin et al. [10]. The material model used in FE modeling can be established based on either the constitutive model or the stress–strain data obtained from the experiment, or by selecting a material with the same or similar grade from the material library of the software. For convenience, DIN_CuZn40Pb2, which is very similar in composition and performance to CuZn39Pb2, is selected from the material library as the material model for FE simulation. The temperature range of DIN_CuZn40Pb2 material model is 500 ~ 900 °C, and the strain rate range is 0.3 ~ 100 s^{-1}. To ensure reliable simulation results, the temperature and strain rate of the workpiece throughout the forming process must fall within a consistent range that reflects actual conditions. Therefore, initial workpiece temperature and punch speed are critical parameters in forging forming FE simulations. In Ref. [9], Yin et al. obtained that the optimal forging temperature of CuZn39Pb2 is 690 ~ 720 °C, and the optimal forging strain rate is 1 ~ 3 s^{-1} by means of isothermal hot compression tests and processing maps. Therefore, the initial temperature of the workpiece is set as 700℃ in both the actual production and FE model. In the isothermal hot compression tests, the relationship between the real strain rate $\dot{\varepsilon}$ and the linear compression speed v is $\dot{\varepsilon} = v/h$, where h is the instantaneous height of the specimen. The original height of the specimen is 15 mm, and the maximum compression is 60%, so the range of h is 6 ~ 15 mm. Therefore, the range of the corresponding optimal linear compression speed v is 6 ~ 45 mm·s^{-1}. In actual production, the speed of each hydraulic slider of the multicore forging press can be adjusted separately. Considering the production efficiency, equipment control accuracy, and the above analysis results, the actual punch speed is 50 mm·s^{-1}, which is also the punch speed set in the FE model. When setting simulation parameters, it is important to consider the actual production situation when determining the friction coefficient and heat transfer coefficient between the rigid dies and punches and the copper alloy workpiece. Due to high contact pressure in the closed die forging process of copper alloy valve bodies, a shear model is selected as its friction type. In practical applications, atomized graphite-based lubricant is sprayed on the surface of the die, punch, and workpiece to reduce the resistance of material flow. According to the research results of Hartley and Pillinger [11] and Khaimovich et al. [12] and the production experiences, the friction coefficient is set as 0.3 in this paper. When the copper alloy valve body is forged, the initial temperatures of the die and punch are 450 °C, which is lower than the workpiece's initial temperature of 700 °C. Therefore, heat transfer occurs on all contact surfaces between the workpiece and the die and punch during the forming process. In the Deform-3D software, the contact between the objects is selected as the forming process, and the heat transfer coefficient defaults to a constant value of 5 KW/(m·°C) [13]. In order to ensure the accuracy of simulation and the efficiency of calculation at the same time, the initial workpiece is divided into 80,000 elements. The initial element size is between 0.886208 and 1.77242 mm, and when the interference depth is 0.7 times the relative element size, the elements will be automatically remeshed to make them smaller. The software is capable of adaptively remeshing the local mesh during the deformation process

Table 1 Parameters of FE model

Initial temperature of workpiece	700 °C	Friction type	Shear
Initial temperature of die	450 °C	Friction value	0.3
Number of elements	80,000	Punch speed	50 mm/s
Heat transfer coefficient	5 KW/(m·°C)	Inter object	Die and workpiece

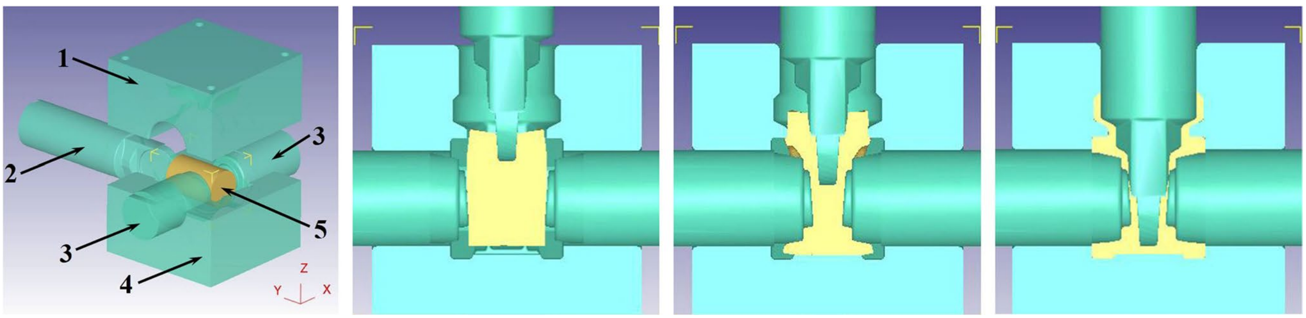

Fig. 2 Schema of punches position for round cross-section workpiece; 1, top die; 2, central punch; 3, side punch; 4, bottom die; 5, copper alloy workpiece with round cross-section

and automatically compensating for volume loss resulting from such remeshing, leading to a slightly higher number of elements than initially set. To avoid prolonging FE simulation time, the valve body's logo and mark are removed from both the top and bottom dies. Relevant parameters for FE simulation are presented in Table 1.

3 Results and discussion

3.1 Forming process using round cross-section workpiece

The workpiece with a round cross-section is the most commonly used raw material for forging copper alloy valve bodies. According to the digital geometric model of the copper alloy valve body, its volume is 132,653 mm^3, and the minimum hole diameter of the mold cavity is 48.6 mm. Therefore, a round cross-section workpiece with a diameter of 48 mm and a length of 73.3 mm was selected as the starting log. The geometry of the valve body studied in this paper is close to the valve body with a nominal diameter of 25 mm studied by Yin et al. [8]. Referring to the FE simulation and experimental research results, the punch action sequence is set as follows.

At the beginning, all three punches make contact with the workpiece, and the side punches are positioned to clamp the workpiece. The central punch initiates movement first while the side punches remain stationary. Once the central punch has reached 35% of its total stroke, the side punches begin to move. While this occurs, the central punch continues to press down until it reaches the set stroke.

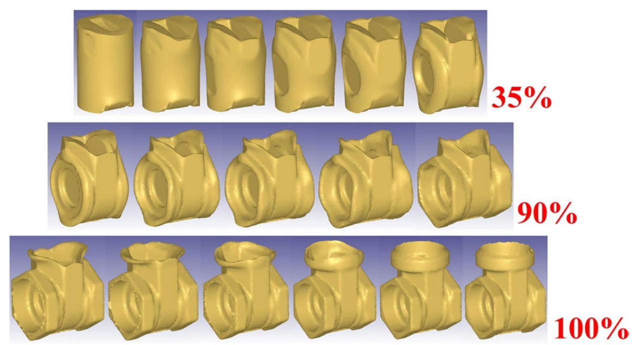

Fig. 3 Progress of valve body formation in case of cylindrical initial copper alloy log

When the raw material is a round cross-section workpiece, the initial position and movement position of the punches are shown in Fig. 2. The central punch moves in -Y-direction, and the side punches move in ± X-direction.

The forged valve body using a round cross-section workpiece is depicted in Fig. 3. It can be observed that during the initial stage of deformation, the central punch pushes the workpiece to the bottom of the cavity, resulting in deformation of both the outer surface of the valve body bottom and the central valve hole. As the central punch moves down, resistance in the *Y*-direction increases, leading to material beginning to flow in the ± X-direction. Although the side punches remain stationary at this point, they still start to deform the side valve hole of the valve body. Since the central valve hole has an approximately hexagonal shape, which is quite different from the round cross-section, the distribution and flow of the metal in the center are uneven.

At the initial stage of forming, there is an obvious height difference on the end surface of the central valve hole. As the side punches begin to move, the combined action of the three punches makes the side valve holes further elongate. Because the outer diameter of the side valve hole is hexagonal and the inner diameter is circular, the metal flow during the side valve hole forming is also uneven. The metal flow velocity at the upper and lower ends of the side valve hole is higher than that at the side, where a slower flow rate is observed. Forming defects are more likely to occur in areas with large velocity gradient. However, due to sufficient metal flow, the end face of the side valve hole is filled first before that of the central valve hole, reducing potential defects on the end face of the side valve hole. Before the end face of the side valve hole is completely filled, there always exists a significant velocity gradient in the metal within the central valve hole. Once the end face of the side valve hole is completely filled, the height difference of the central valve hole begins to decrease and metal starts flowing radially towards the central valve hole. As soon as the central punch moves further down, the end face of the central valve hole is finally formed.

Unfortunately, from the FE simulation result, we observed an obvious crack defects at the central valve hole, as shown in Fig. 4a. The same forging experiment consistent with the FE simulation was carried out on a multicored forging press, and the experimental result as shown in Fig. 4b. At the central valve hole of the experimental forging valve body, in addition to obvious cracks, significant fold, wrinkle, and depression can be observed. We speculate that the crack is the extreme case of the above defects, which is caused by the uneven flow of metal. The FE simulation results are consistent with the experimental results.

Figure 5 is the FE simulation results at the final forming stage for the valve body forged by a round cross-section workpiece. Figure 5a is the velocity field. It can be seen that the largest velocity vectors at the end faces of the central valve hole are along the Y-direction, that is, the metal flows to the end face of the central valve hole under the reverse extrusion of the central punch until it is filled. However, at the crack position, the velocity vectors are obviously inclined and faster than the surrounding velocity, indicating that this part of the metal does not flow in the ideal direction, which is the main reason for the crack. Figure 5b is the temperature field. The temperature of the valve body at the final stage of forging is about 650 °C, which is nearly 50 °C lower than the initial temperature of the workpiece. Although the temperature at the defect is slightly higher than the surrounding temperature, the large overall temperature drop and the local uneven flow make the oppositely confluent metals unable to bond tightly, which eventually leads to the crack. The extremal regions shown in Fig. 5 c and e are identical, indicating that the stress and strain rate correspond to each other in positive proportion. Usually, the extremal regions of stress and strain rate are the last filled location. The extremal regions in Fig. 5 c and e are located at the neck and the end face of the central valve hole, the end face of the side valve hole, and the bottom of the valve body, indicating that these regions are filled last. Figure 5d shows that at the final stage of the valve body, forming the effective strain of the whole valve body is uniform. The value of the effective strain is about 3.3, which is a relatively large deformation.

Through the analysis of the FE simulation results and the experimental results, it is found that the uneven metal flow at the end of the central valve hole is the primary cause of fold and crack. As shown in Fig. 3, during the initial forging stage, significant differences between the cross-section areas of the central punch and the workpiece result in uneven metal distribution. Improving this initial distribution would lead to more uniform metal flow throughout forming processes, and the defects can be avoided.

3.2 Forming process using hexagonal cross-section workpiece

The aforementioned FE simulation results demonstrate that the uniform distribution of materials during the initial stage of deformation has a significant impact on the final forming quality, which aligns with the original purpose of utilizing preformed blanks in traditional forging processes. Therefore, altering the cross-sectional shape of the initial workpiece can enhance metal flow and distribution during valve body

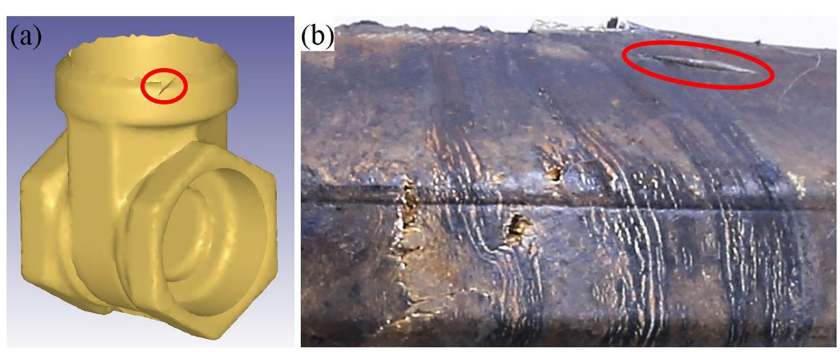

Fig. 4 Crack defects at the central valve hole: **a** FE simulation result; **b** experimental result

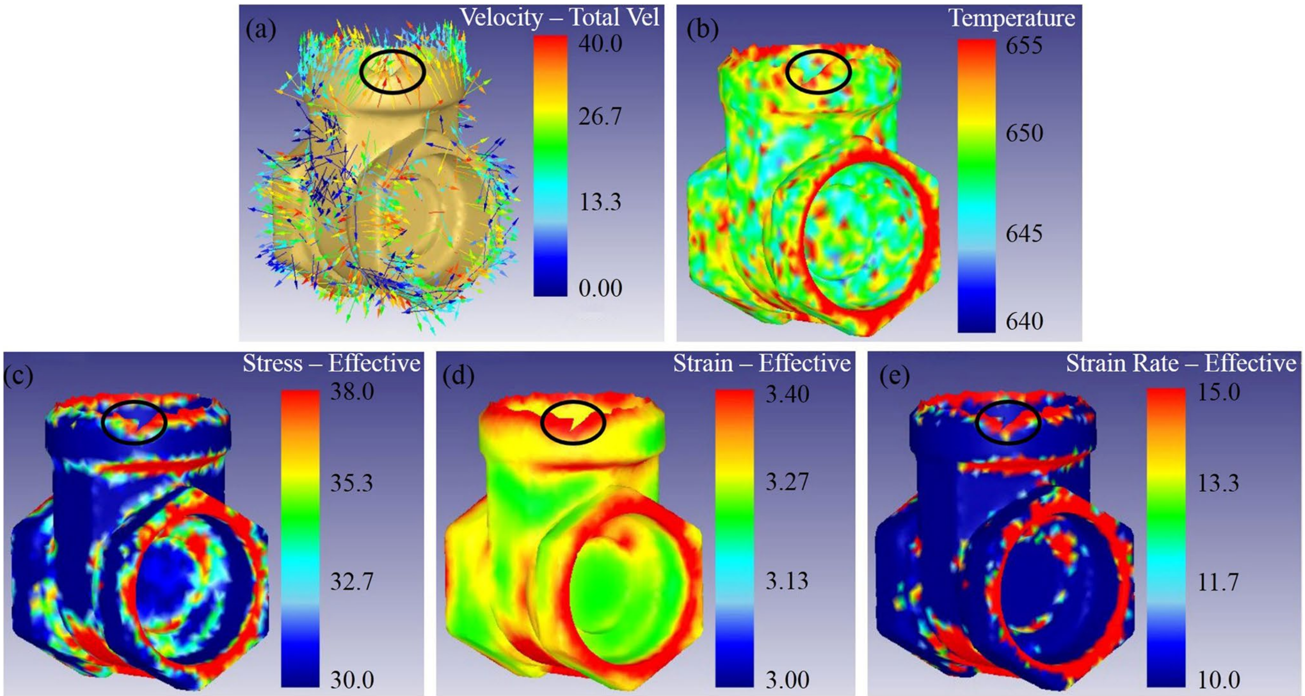

Fig. 5 FE simulation results for round cross-section workpiece: **a** velocity; **b** temperature; **c** effective stress; **d** effective strain; **e** effective strain rate

forming processes. In established industrial production settings, raw material manufacturers are capable of providing customized solutions. In order to validate this concept without altering the die and simulation parameters, the cross-section of the initial workpiece was transformed into a hexagon with dimensions similar to those of the central valve hole (as depicted in Fig. 6). The length of the initial workpiece is calculated as 87 mm. Since the hexagonal cross-section workpiece will not tilt and rotate during the top die clamps with the bottom die, the initial position of the side punches is set to be 10 mm away from the workpiece surface to facilitate the ± X-direction flow of the metal. When the central punch reaches 30% of its total stroke, the side punches begin to move at an equivalent speed as the center punch. For a hexagonal cross-section workpiece, the initial position and movement position of the punches are shown in Fig. 7.

Figure 8 depicts the forging process of the copper alloy valve body utilizing a hexagonal cross-section workpiece. The figure illustrates that there is no discernible height difference at the end of the central valve hole during the forming process. Although the end face of the side valve hole is filled first, the unevenness of the metal flow at the side valve hole is alleviated. Once both side valve holes are full, the end face of the central valve hole also has been substantially formed. The deformation process employed here effectively eliminates the occurrence of crack and wrinkle on the end face of the central valve hole. During the final stage of forming, a small amount of metal is extruded from the gap between the central punch and the cavity, which protrudes beyond the end face of the central valve hole. As downward pressure from the central punch continues, this excess metal is subsequently

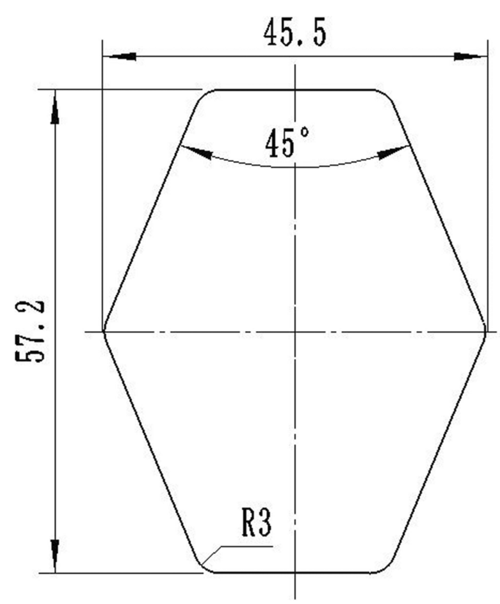

Fig. 6 Shape and size of hexagonal cross-section workpiece

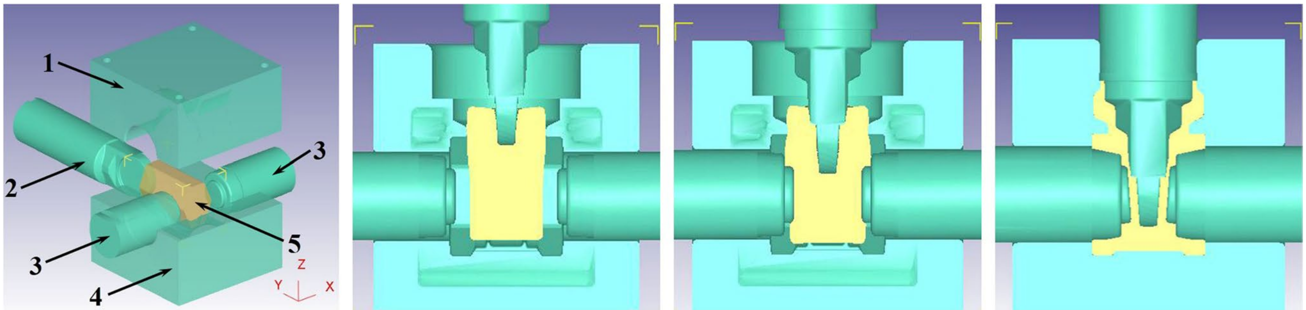

Fig. 7 Schema of punches position for hexagonal cross-section workpiece; 1, top die; 2, central punch; 3, side punch; 4, bottom die; 5, copper alloy workpiece with hexagonal cross-section

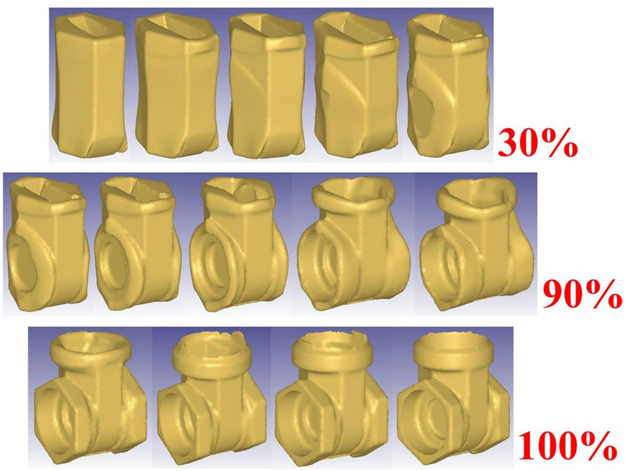

Fig. 8 Progress of valve body formation in case of hexagonal initial copper alloy log

Fig. 9 Valve body forged by CuZn39Pb2 continuous casting workpiece with a hexagonal cross-section

squeezed down until it becomes flush with the end face of the central valve hole.

Figure 9 depicts a valve body forged by CuZn39Pb2 continuous casting workpiece with a hexagonal cross-section on multicored forging press. The valve body exhibits a complete appearance, smooth and clean surface, absence of cracks or wrinkles, and minimal flash overflow. Experimental results are consistent with the FE simulation outcomes, while the strength of the valve body surpasses 20% of the standard strength after inspection. The experimental results confirm the significance of workpiece shape and size, as well as punch action sequences, to SPSC.

Figure 10 is the FE simulation results at the final stage of the valve body forming using a hexagonal cross-section workpiece. For comparison, the same scale is used in Figs. 10a and 5a. As can be seen from Fig. 10a, the velocity vectors of the end face of the three valve holes are basically perpendicular to the valve hole planes. The direction of the velocity vector is smoother than that in Fig. 5a, and there is no obvious cross velocity vector. The arrow colors representing the metal flow velocity is also dominated by dark blue and light blue, indicating that the cavity has been basically filled in the final stage of forming, and the material flow is relatively slow. There are individual elements at the bottom of the valve body and the end face of the side valve hole showing red arrows, indicating that these are the last full position.

Figure 10b is the temperature field of the valve body forming using a hexagonal cross-section workpiece, and its scale range is 35 °C higher than Fig. 5b. The temperature of the valve body is uniform, about 680 °C, which is only 20 °C lower than the initial temperature of the workpiece, and about 30 °C higher than the temperature of the valve body formed with the round cross-section workpiece. Since the initial temperature of both the workpiece and die are identical in both schemes, differences in final temperatures arise from variations in deformation processes. Temperature comparison results indicate that a reasonable cross-sectional shape for the workpiece can enhance metal flow efficiency, thereby reducing heat loss

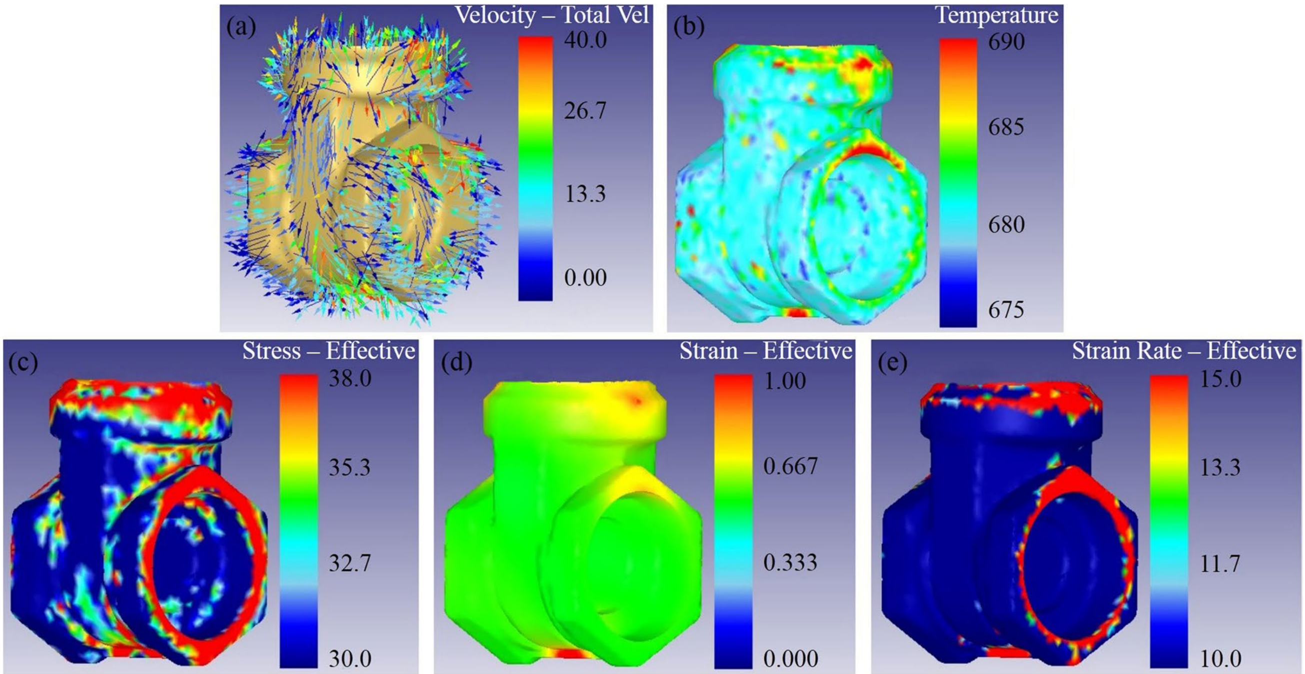

Fig. 10 FE simulation results for hexagonal cross-section workpiece: **a** velocity; **b** temperature; **c** effective stress; **d** effective strain; **e** effective strain rate

during material deformation and maintaining high temperatures throughout forging processes, ultimately mitigating risks associated with forming defects.

The stress scale in Fig. 10c is identical to that in Fig. 5c, and the final stress distribution is basically similar; that is, the stress at the end face of the central valve hole, the end face of the side valve hole, and the bottom of the valve body is larger, while the stress in other positions is smaller. Notably, a significant decrease in stress occurs at the neck of the central valve hole due to changes made to the initial workpiece's cross-section, resulting in an improved final stress distribution.

Due to the improvement of the deformation process, the final strain of the copper alloy valve body using a hexagonal cross-section workpiece is overall smaller than that of the copper alloy valve body using a round cross-section workpiece. For the convenience of observation, the strain scale of Fig. 10d is different from that of Fig. 5d. As shown in Fig. 10d, the maximum strain appears at the reinforcing rib of the valve body bottom, about 1.5. In addition, there are also local areas with slightly larger strain at the end face of the central valve hole and the end face of the side valve hole. But the overall strain distribution of the valve body is uniform, about 0.5. The original design intention of this position is to improve the strength of the valve body through a 2×1.5 mm reinforcing rib. However, the FE simulation results show that the reinforcing rib increase the difficulty and risk of the valve body forming, which is more harmful than beneficial. This reinforcing rib can be optimized or removed in the subsequent product development.

The stress scale in Fig. 10e is the same as that in Fig. 5e. Compared with Fig. 5e, the neck of the central valve hole is no longer the area where the ultimate strain rate occurs, and the overall distribution of strain rate in the valve body is more uniform. Figure 10e shows that the end face of the central valve hole, the end face of the side valve hole, and the bottom of the valve body are the last filled areas, which is consistent with the results of Fig. 5e.

3.3 Analysis of microstructure

Figure 11 shows the metallographic photos of the central valve hole, the side valve hole, and the side wall of the valve body formed by round cross-section workpiece and hexagonal cross-section workpiece respectively. The white region represents the Cu-rich phase, and ImageJ software was utilized to determine the dimensions of this phase in six metallographic images shown in Fig. 11. The average values of both the long and the short axes of the Cu-rich phase were measured, as shown in Table 2. The results indicate that the Cu-rich phase in the valve body formed by a hexagonal cross-section workpiece has a slightly smaller average size. According to the findings in Ref. [9], a smaller size of the Cu-rich phase is more

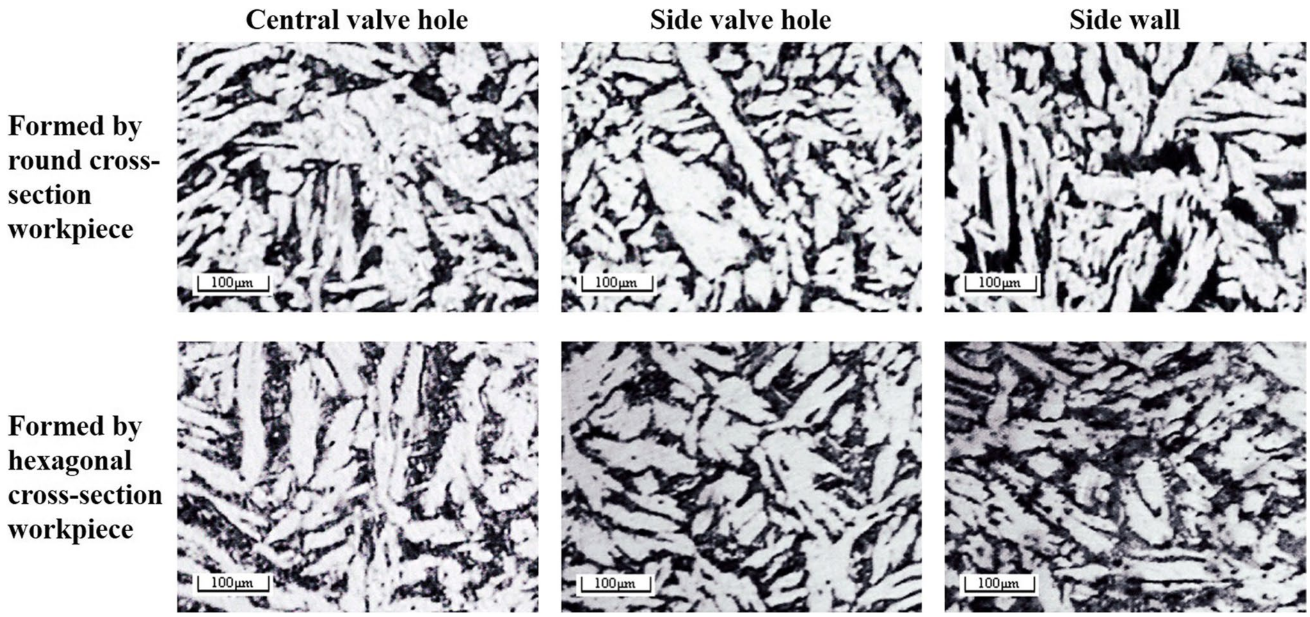

Fig. 11 Metallographic photos of different positions of valve bodies formed by different bar cross-sections

Table 2 Sizes of Cu-rich phase

	Central valve hole		Side valve hole		Side wall	
	Long axis (μm)	Short axis (μm)	Long axis (μm)	Short axis (μm)	Long axis (μm)	Short axis (μm)
Formed by round cross-section workpiece	159.64	34.21	108.93	31.43	106.07	36.29
Formed by hexagonal cross-section workpiece	130.71	28.93	95.02	27.86	84.98	27.85

advantageous for the microstructure refinement of copper alloys. To be frank, no significant discrepancy can be discerned among the six images depicted in Fig. 11. The longitudinal comparison reveals that the impact of the initial workpiece cross-sectional shape on the material microstructure is limited, while the horizontal comparison demonstrates a fundamentally uniform microstructure in the valve body. The reason for the indiscernible discrepancy lies in our establishment of reasonable forging process parameters, including optimal workpiece temperature, die temperature, and punch speed based on the properties of CuZn39Pb2 copper alloy in both FE simulation and experiment. Therefore, despite the differences in metal flow processes between the two cases, the microstructure of materials is minimally affected due to consistent process conditions. Additionally, optimized process parameters result in a more uniform microstructure of formed parts, thereby reducing variations in metallographic structure across different positions of the valve body and ultimately enhancing mechanical properties.

4 Conclusions

The research presented in this paper demonstrates that the process parameters of closed die forging encompass not only workpiece temperature, die temperature, and punch speed but also the cross-sectional shape of the workpiece and the action sequence of punches, which are often overlooked despite their significance. The cross-sectional shape of the workpiece and the action sequence of punches directly impact velocity, temperature, stress, strain, and strain rate during valve body forming. These factors not only determine the filling process and shape accuracy of the valve body, but also have a significant impact on the microstructure of the material. In this paper, both the FE simulation results and experimental findings demonstrate that optimal appearance quality for valve body production can be achieved while avoiding forming defects through altering the cross-sectional shape of the workpiece and adjusting the action sequence of punches under reasonable conditions of workpiece temperature, die temperature, and punch speed. Meanwhile, appropriate process parameters can ensure the superior microstructure of the material, thereby enhancing the macroscopic mechanical properties of the valve body. This process achieves the SPSC in closed die forging of large-diameter copper alloy valve body.

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Author contribution Yin Jing designed the work, processed the experimental data, and drafted the article. Wu Haibao did the preparation for the experiment. Shu Xuedao made a critical revision of the article.

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Declarations

Competing interests The authors declare no competing interests.

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