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OPTIMIZATION OF DEFECT PREVENTION IN HOT FORGING OF CuZn40Pb2 BRASS ALLOY WATER VALVE COVERS: A FINITE ELEMENT AND EXPERIMENTAL APPROACH

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ABSTRACT

This study explores the hot forging process of CuZn40Pb2 brass alloy water valve covers through a combination of finite element modeling and experimental trials. Key factors influencing defect formation, such as the cylindrical workpiece geometry and die temperature, are examined in detail. Simulations using Deform 3D software focused on the impact of temperature on material flow behavior, incorporating inputs such as geometry, filling sequence, and applied force. Experimental findings underscored the crucial role of the friction coefficient, which diminishes with the use of lubricants, in controlling material flow. The reduction in friction, caused by heat generated from die friction during forging, was found to elevate the risk of defects. Stress and strain analysis from the simulations revealed a complex interaction between temperature and friction, significantly affecting defect formation. The strong correlation between simulation and experimental results confirmed the value of computational modeling in predicting and preventing defects. This research provides valuable insights into optimizing hot forging parameters for CuZn40Pb2 brass alloy components, enabling improvements in product quality and process efficiency.

1. INTRODUCTION

Hot forging is a widely used manufacturing method that involves applying high temperatures, significant pressures, and forceful impacts within enclosed dies [1-3]. This adaptable process is essential for producing complex components with high geometric precision and accounts for over sixty percent of all industrial parts [4]. By effectively combining heat, pressure, and controlled shaping, hot forging enables various industries to manufacture crucial parts, from automotive components to aerospace hardware, highlighting its vital importance in contemporary manufacturing [5-7].

Key factors such as temperature regulation, raw material shape, and die design are critical in reducing production costs and improving the quality of forged products [8, 9]. However, relying solely on traditional empirical methods for component design and production can be challenging and expensive. To overcome these issues, researchers advocate for a systematic approach to optimizing both part and die design in hot forging processes [10]. By utilizing advanced computational tools like finite element modeling (FEM) software, they can accurately simulate and analyze the complex interactions of these variables, enabling data-driven decision-making and refinement of the forging process [11,12]. This transition toward data-driven optimization enhances cost efficiency and ensures compatibility with other production techniques, paving the way for improved efficiency and quality in the metal forging industry.

Historically, the industrial production process has depended heavily on the skills of designers and trial-and-error experimentation, which can be both costly and time-consuming. To overcome these challenges, finite element modeling (FEM) software applications - such as ANSYS, Abaqus, Deform® 3D [13-15], and Marc - have become increasingly popular for evaluating and enhancing the efficiency of metal forming processes. This shift has resulted in substantial reductions in both production costs and time. Researchers have employed FEM simulation algorithms to examine various factors in metal forming, including deformation loads and metal flow behavior [16-18]. In this study, the Deform® 3D finite element method simulation software was utilized to model the hot forging process of a CuZn40Pb2 brass valve body cover using closed die forging, aiming to clarify the impact of temperature on the forming characteristics.

2. EXPERIMENTAL

This study utilized a lead-reduced brass alloy with a CuZn40Pb2 composition, which is commonly preferred for water valves due to health considerations. The chemical composition of this brass alloy is presented in Table 1.

Figure 1(a) shows the technical drawing of the valve cover studied in this research. The initial billet dimensions

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before forging are 68.2 mm in height and 50 mm in diameter. After the forging process, the height is reduced to 35.42 mm, and the width increases to 111.32 mm. Figure 1(b) illustrates the entire forging process from start to finish. For the traditional forging of the valve, a hydraulic press with a capacity of 150 tons was employed. The billet was heated to 700°C, while the die was maintained at 350°C, and the press operated at a speed of 10 millimeters per second.

Table 1 *Chemical Composition of CuZn40Pb2*

Element	Cu	Pb	Fe	Sn	Ni	Al	Si	Cd	Zn
wt%	58.2	1.75	0.28	0.20	0.069	0.003	0.002	0.002	Balance

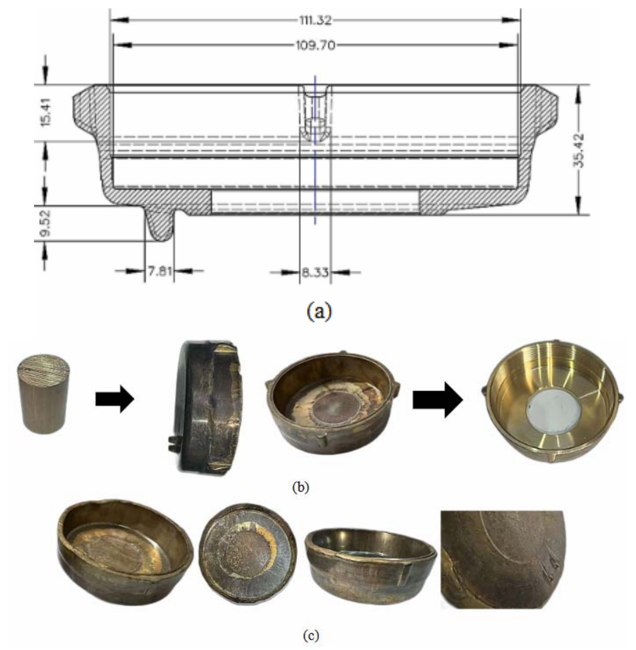

Fig.1. (a) Drawing of body cover, (b) Forging of the brass body cover from start to finish, (c) Defective parts formed during the forging process

Figure 1(c) illustrates the imperfections that occurred after hot working in a closed die, which is the primary focus of this study. The figure highlights a variety of defects, including:

- Deformations of the external surface of the valve cover: These may arise from uneven heating of the billet, misalignment of the dies, or excessive forging parameters.
- Failure to achieve the desired geometric accuracy: This issue can stem from billet misalignment, die wear, or improper forging conditions.
- Distortions of the mouthpiece of the cover: These distortions may result from excessive forging pressure or inadequate die design.
- Incomplete filling of the lower two teeth: This defect can be caused by insufficient forging pressure or poor die design.
- Incomplete filling of the four ears on the sides: Similar to the lower teeth, this issue can also result from insufficient forging pressure or improper die design.
- Excessive oxidation beneath the cover: High forging temperatures or inadequate lubrication can lead to this problem.
- Adhesion between the die and the product after hot working: This can occur due to improper lubrication or excessive forging pressure.

3. FINITE ELEMENT MODEL

In this work, we will not delve into a comprehensive discussion of the finite element formulation for the rigid-viscoplastic metalworking process in DEFORM® 3D software. Equation 1 presents the general variational principle-based equation for solving the rigid-viscoplastic field equations:

$$\delta_{\varphi} = \int_{v} \sigma_i \delta\dot{\varepsilon}_i dv + \int_{v} K\dot{\varepsilon}_v \delta\dot{\varepsilon}_v dv - \int_{SF} F_i \delta u_i ds = 0 \qquad (1)$$

In this equation, ε_i and σ_i represent the effective strain and effective stress, respectively; SF is the surface force; u_i indicates the surface velocity components; F_i is the traction stress; ε_v denotes the volumetric strain rate; v represents volume; and K is a significant positive penalty constant. Through a discretization process, Equation 1 is transformed into a nonlinear algebraic equation suitable for finite element analysis, with solutions obtained iteratively [19].

Several assumptions were made regarding the hot forging process. Due to negligible elastic deformation, the dies were modeled as rigid bodies. Given that the elastic deformation of the hot-forged material is minimal and can be disregarded, it is assumed that the material undergoes complete plastic deformation. The shear friction model was employed, defined as follows:

$$F_S = \mu * k \qquad (2)$$

where F_S represents the frictional stress, μ is the friction coefficient, and k is the shear yield stress.

This investigation utilized DEFORM 3D v10.2 software to simulate the hot forging of a cylindrical billet made from CuZn40Pb2 brass, sourced from the software database. The billet measured 50 mm in diameter and 68.2 mm in length. The valve body material was identified as CuZn40Pb2, corresponding to the DIN_CuZn40Pb2 classification in the library, with the flow properties for the simulation under hot conditions detailed in Figure 2. The experimental forging temperature of 700°C falls within the material model's range of 550-950°C. The forging simulation was conducted at temperatures varying from 600°C to 750°C, maintaining a constant strain rate of 1 s^{-1}. This temperature range is commonly employed in industrial hot forging processes for brass.

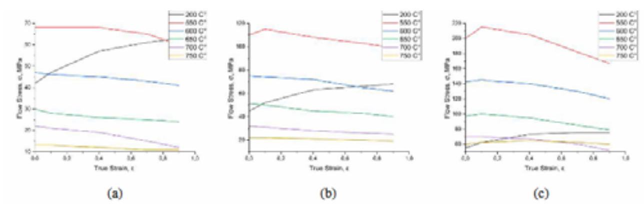

Fig. 2. Hot working strain curves at different temperatures and strain rate of (a) 0.1 s^{-1}, (b) 3 s^{-1} and (c) 100 s^{-1}

The geometric model was created using the ZW3D CAD software and exported in .stl format, incorporating the DRX volume fraction and constitutive model for input into the DEFORM-3D finite element software [20], as shown in Figure 3. Both the upper and lower dies were modeled as rigid bodies, with the upper die assigned a velocity of 5 mm/s while the lower die remained stationary. The current investigation utilized the finite element method (FEM) to simulate the deformation process, taking into account the relevant physical properties of the billet. Specifically, the billet was discretized into 84,462 tetrahedral elements and 18,184 nodes, with a refined mesh applied throughout the specimen volume to enhance simulation accuracy.

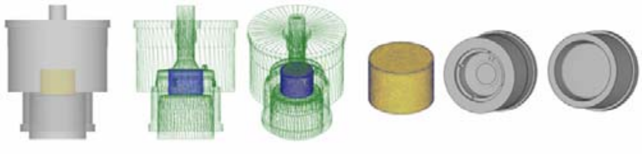

Fig. 3. Imported dies and meshed parts

4. RESULTS AND CONCLUSION

The finite element method (FEM) simulation of the complete forging process took 3.8 seconds. Figure 4 illustrates the variation in effective stress distribution and deformation over time. At 1.80 seconds, the valve cover maintains its billet shape, with an effective stress of 7.05 MPa at the contact points during deformation. By 3.37 seconds, the effective stress in the lower threads rises to 10.4 MPa. At 3.77 seconds, the lower teeth are fully filled, although the four lateral protrusions have not yet achieved complete filling, with an effective stress of approximately 11.6 MPa at this point. By the end of the process at 3.80 seconds, the forging is complete, with an effective stress of 12 MPa, as the die begins to retract. Notably, the valve cover rim thins during deformation, resulting in a lower stress of 7.2 MPa in that region.

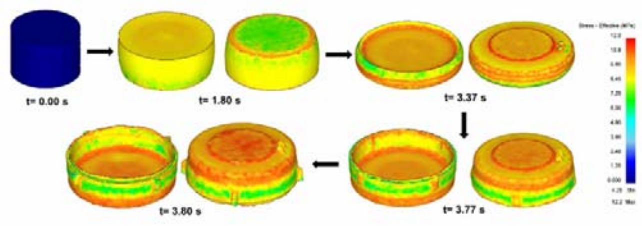

Fig. 4. Effective stress distribution at t=0.00 s; t=1.80 s, t=3.37 s, t=3.77 s, t =3.80 s

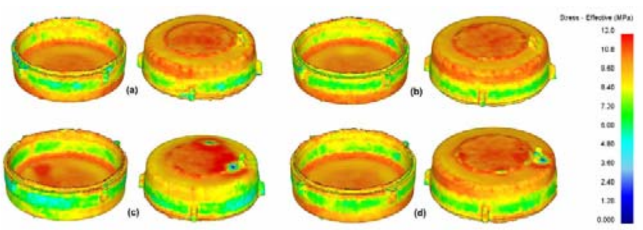

Fig. 5. Effective stress distribution at different billet temperatures with constant die temperature(350℃), (a) billet temperature 750℃, (b) billet temperature 700℃, (c) billet temperature 650℃, (d) billet temperature 600℃

The hot deformation process is highly influenced by the forging temperature, particularly with respect to the metal flow behavior. As shown in Figure 5, the effective stress distribution in the deformed billet is non-uniform, with the regions of lower strains exhibiting the highest levels of effective stress (Rahul et al., 2018). At temperatures above 700°C, the material flow and stress distribution are uniform. However, at 600°C and 650°C, the stress fields are distorted and material flow problems occur. Die adhesion occurred in the blue-colored regions, which is a defect caused by insufficient heating of the billet.

Figure 6 shows the distribution of effective strain on the deformed billet. The deformation is non-uniform, with the edge and side angles exhibiting higher levels of deformation. This heterogeneous deformation is attributed to interfacial frictional forces. The effective expansion value is particularly high in the region of the lower teeth, indicating severe irregularities in the material flow during lower tooth formation. Forging at a billet temperature of 650°C appears to make it difficult to form the lower teeth.

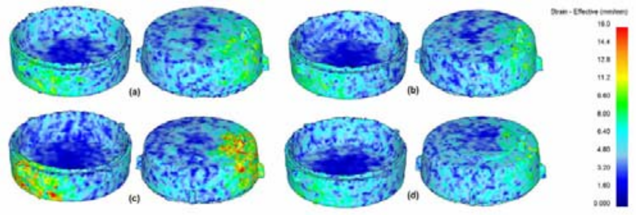

Fig. 6. Effective stress distribution at t=0.00 s; t=1.80 s, t=3.37 s, t=3.77 s, t=3.80 s

The DEFORM 3D FEM simulation analyzed the hot forging process of a water valve cover at temperatures between 600°C and 750°C, with increments of 50°C and a strain rate of 1 s^{-1}. The results revealed non-uniform deformation, with the central region of the billet experiencing concentrated strain, while areas of lower strain showed the highest effective stress. This variability in strain and stress distribution highlighted the process's non-uniformity. Additionally, a direct relationship was found between forging temperature and particle flow rate: as temperature increased, metal flow resistance decreased, leading to a higher particle flow rate. These findings align with industrial practices, demonstrating that simulations can reliably predict metal flow behavior during forging. Future studies will aim to prevent defects by examining additional variables, such as lubricants, press forces, speeds, and expansion rates.

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