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Finite element simulation and experimental study on defects in CuZn40Pb2 brass alloy water valve covers during hot forging

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ABSTRACT

This study investigates the closed-die hot forging process of a CuZn40Pb2 brass alloy water valve cover using a traditional single-stroke forging press. Key factors affecting defect formation in the material geometry include the cylindrical workpiece geometry and die temperature. The finite element model (FEM) developed to optimize temperature effects on material flow behavior was implemented using Deform® 3D software. The simulations considered geometry, filling order, and force as inputs. Experimental trials showed that the coefficient of friction, which decreases with lubricant use, significantly impacts material flow. This is because frictional forces during forging heat the dies, reducing the coefficient of friction and potentially increasing defect likelihood. Stress and strain analysis from the simulations indicated a complex interplay between temperature and friction coefficient, influencing defect formation. The experimental results aligned with the simulations, validating computational modeling as a tool for predicting and mitigating defects. This study offers valuable insights into the closed-die hot forging of CuZn40Pb2 brass alloy water valve covers, emphasizing the importance of temperature and friction control. These findings can improve forging process design and operation, leading to high-quality product production.

1. Introduction

Metal forming through hot forging is a prevalent manufacturing technique characterized by subjecting the material to elevated temperatures, intense pressures, and impactful forces within enclosed dies [4,9,10]. This versatile process serves as the cornerstone for crafting intricate components with exceptional geometric accuracy, making it the bedrock of industrial production, responsible for fabricating more than sixty percent of all industrial components [18]. By harnessing the formidable combination of heat, pressure, and controlled shaping, hot forging empowers industries to create a diverse array of essential parts and components, ranging from automotive components to aerospace hardware, underlining its indispensable role in modern manufacturing [2,11,22].

Temperature control, raw material geometry, and die design play pivotal roles in mitigating production costs and elevating the quality of forged components [3,23]. Nevertheless, relying solely on empirical knowledge to design and manufacture these components can be an arduous and costly endeavor. To address these challenges, researchers emphasize the importance of a systematic approach to optimize both the part and die design in hot forging processes [21]. By leveraging advanced computational tools, such as finite element modeling (FEM) software, they can precisely simulate and analyze the intricate interplay of these factors, allowing for data-driven decisions and fine-tuning of the forging process [24]. This shift towards data-driven optimization not only enhances cost-effectiveness but also ensures compatibility with other production processes, ushering in a new era of efficiency and quality in metal forging industries.

Plastic deformation stands as a foundational pillar in the realm of metalworking, serving as a fundamental process employed to reshape materials and enhance their intrinsic properties [5]. Within the domain of industrial metal forming, numerous techniques harness this process to effect substantial changes in the geometry and characteristics of metallic materials [5]. Prominent among these methods are rolling, forging, extrusion, and drawing, each wielding the power of controlled plastic deformation to fashion an array of components and products [8]. Whether it is the elongation and thinning of metal sheets in rolling, the precision shaping of intricate parts through forging, the extrusion of intricate profiles, or the elongation of wire and tubing in drawing, these processes exemplify the artistry of molding metal to meet diverse industrial needs, all rooted in the transformative magic of plastic deformation [13].

Forging represents a multifaceted manufacturing process marked by the imposition of formidable stresses and deformation forces, resulting in a nuanced and intricate material flow during deformation analysis [16]. The distribution of flow stress and strain within the material matrix is contingent on a multitude of factors, including the applied strain, strain rate, and the temperature at which the deformation occurs [6]. To elucidate and optimize these complex dynamics, physical modeling methodologies, exemplified by the deployment of specialized equipment like Gleeble® [20] thermomechanical simulators, have become invaluable in industrial settings. However, while these simulators offer valuable insights, their optimization poses challenges due to factors such as the generation of frictional heat, which can significantly impact flow behavior, introduce unpredictability, and contribute to non-uniformity in the overall production process [26], underscoring the need for meticulous control and calibration in pursuit of optimal forging outcomes.

Traditionally, the industrial production process has relied on the expertise of designers and trial-and-error experimentation, which can be costly and time-consuming. To address this, FEM software applications, such as ANSYS, Abaqus, Deform® 3D [19], and Marc, have been increasingly used to assess and improve the efficiency of metal forming processes [25]. This has led to significant reductions in production costs and time. Researchers have used FEM simulation algorithms to investigate various aspects of metal forming processes, such as deformation loads and metal flow behavior [1,7,17]. In the present investigation, the Deform 3D finite element method simulation software was used to model the hot forging process of a CuZn40Pb2 brass valve body cover using closed-die forging. The aim was to elucidate the influence of temperature on forming characteristics.

2. Experimental procedure

This study employed a lead-reduced brass alloy of the CuZn40Pb2 composition. Lead-reduced brass valves are generally preferred in water valves for the sake of human health. The chemical composition of the brass alloy is detailed in Table 1 [14].

Figure 1a illustrates the technical drawing of the valve cover, the subject of this research. The initial billet height prior to forging is 68.2 mm and the diameter is 50 mm. After forging, the height is 42.50 mm and the diameter is 111.32 mm. Figure 1b also depicts the progression of the forging process from beginning to end. For the traditional forging of the valve, a hydraulic press with a capacity of 150 tons was used. The billet temperature was 700 °C and the die temperature was 350 °C. The press operated at a speed of 5 mm/s.

Figure 1c depicts the imperfections that arose following hot working in a closed die, which is the focus of this study. The figure reveals a multiplicity of defects, including:

• Distortions of the mouthpiece of the cover: this can be caused by excessive forging pressure or improper die design (Fig. 1c (1,2)).

• Failure to achieve the desired geometric accuracy: this can be attributed to factors such as misalignment of the billet, wear on the dies, or improper forging conditions (Fig. 1c (3)).

• Excessive oxidation beneath the cover: this can be caused by high forging temperatures or insufficient lubrication (Fig. 1c (4)).

• Deformations of the external surface of the valve cover: this can be caused by uneven heating of the billet, misalignment of the dies, or excessive forging parameters (Fig. 1c (5)).

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

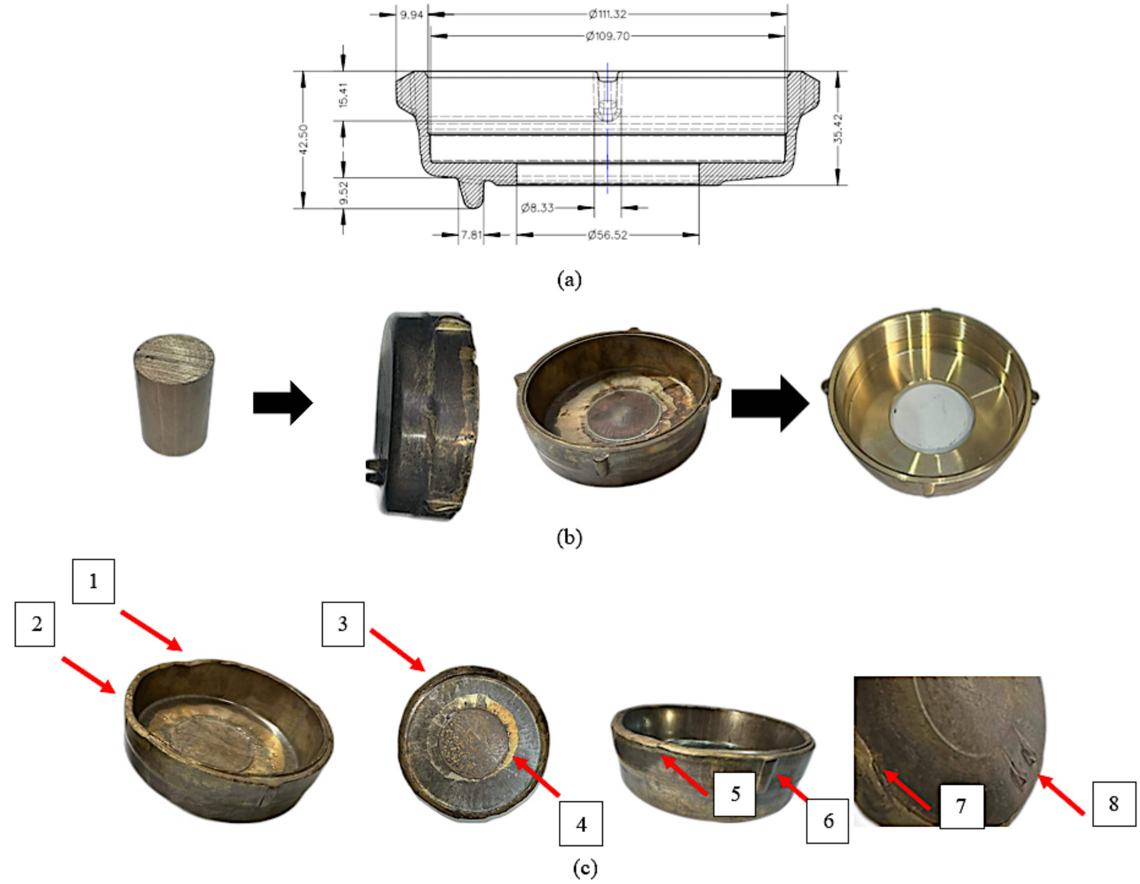

Fig. 1. Technical drawing of the valve cover (a), forging of the brass body cover from start to finish (b), and defective parts formed during the forging process (c).

• Incomplete filling of the four ears on the sides: this can be caused by insufficient forging pressure or improper die design (Fig. 1c (6)).

• Adhesion between the die and the product after hot working: this can be caused by improper lubrication or excessive forging pressure (Fig. 1c (7)).

• Incomplete filling of the two lower teeth: this can be caused by insufficient forging pressure or improper die design (Fig. 1c (8)).

These imperfections can impair the design geometry of the valve cover, and may also lead to leaks and other functionality problems. It is of critical importance to identify and address the root causes of these defects in order to manufacture high-quality valve covers.

3. Finite element model

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

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

In Eq. (1) above, ε_i and σ_i represent the effective strain and effective stress, S_F represents the surface force, u_i represents the surface velocity components, F_i represents the traction stress, $\dot{\varepsilon}$ represents the volumetric strain rate, v represents the volume, and the variable K represents a significant positive penalty constant. By means of a discretization process, Eq. (1) is transmuted into a nonlinear algebraic equation suitable for finite element analysis. The solution to the resulting simultaneous equations is obtained iteratively.

The geometric model created using the ZW3D CAD software system and the DRX [12] volume fraction and constitutive model was input into the DEFORM 3D finite element software in .stl format for simulation, as depicted in Fig. 2. A number of presumptions were made for the hot forging

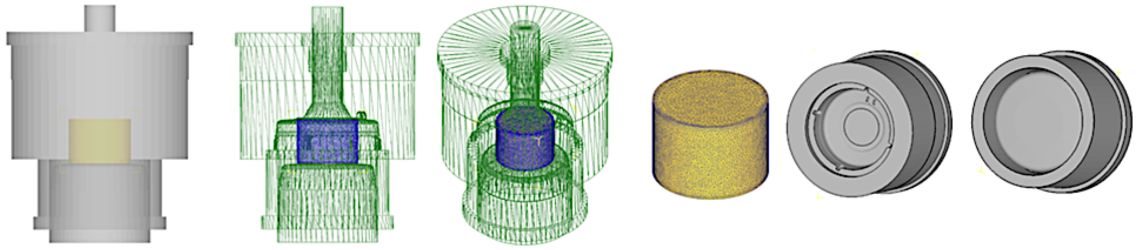

Fig. 2. Imported dies and meshed parts.

process; owing to the insignificant elastic deformation, the dies were modeled as rigid bodies. Since the elastic deformation of a hot-forged material is very small and hence negligible, it is assumed that the material undergoes complete plastic deformation. The shear friction model was selected as the friction model, and its definition is as follows:

$$F_s = \mu * k, \tag{2}$$

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

The upper and lower dies were modeled as rigid bodies. The upper die was assigned a velocity of 5 mm/s, while the lower die was held stationary. The present investigation employed the finite element method (FEM) to simulate the deformation process, accounting for 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.

This investigation used the DEFORM 3D v10.2 software to simulate the hot forging of a cylindrical billet of CuZn40Pb2 brass, retrieved from the software database. The billet had the dimensions of 50 mm in diameter and 68.2 mm in length. The experimental material of the valve body is defined as CuZn39Pb2, corresponding to the DIN CuZn40Pb2 material classification in the library, and the flow properties of the material to be used for the simulation at hot conditions are given in Fig. 3. The experimental forging temperature of 700 °C falls within the temperature range of 550–950 °C covered by the material model. The forging simulation was performed at temperatures ranging from 600 °C to 750 °C, with a constant strain rate of $1s^{-1}$. This temperature range is commonly used in industrial hot forging processes for brass.

The investigation adopted the assumption of shear friction between the billet and the die. A coefficient of the friction value of 0.3 was used to represent graphite, a commonly used lubricant between the die and sample, as reported in [15]. It is customary in deformation analysis to neglect the elastic region, as the forging process typically involves significant deformations at elevated temperatures.

The experiment was conducted under isothermal conditions, with the ambient temperature maintained at 20 °C and the die temperature set to 350 °C. In this study, an environmental heat transfer coefficient of 0.05 W/(mm^2·°C) (equivalent to 50 W/m^2·K) was used to estimate the heat exchange between the die and ambient conditions during the forging process. This value, commonly applied in simulations of high-temperature brass forging, is based on standard assumptions reported in the literature. The coefficient of friction for the graphite lubricant was set at 0.3, aligning with values reported in prior studies on forging applications. These parameters were implemented to ensure that the simulation accurately reflected real-world forging conditions. The study employed a Lagrangian incremental simulation approach with a direct method for iteration. The chosen methods for the study were global remeshing, relative interference depth type, and a conjugate gradient solver.

4. Results

The FEM simulation of the complete forging process lasted for 3.80 seconds. Figure 3 depicts the variation of the effective stress distribution and deformation with forging time. The valve cover retains its billet shape at 1.80 seconds, with an effective stress of 7.05 MPa at the contact points during deformation. At 3.37 seconds, the effective stress in the lower threads reaches 10.4 MPa. At 3.77 seconds, the lower teeth are fully filled, but the four lateral protrusions are not yet fully filled. The effective stress at this time is approximately 11.6 MPa. At 3.80 seconds, the forging process is

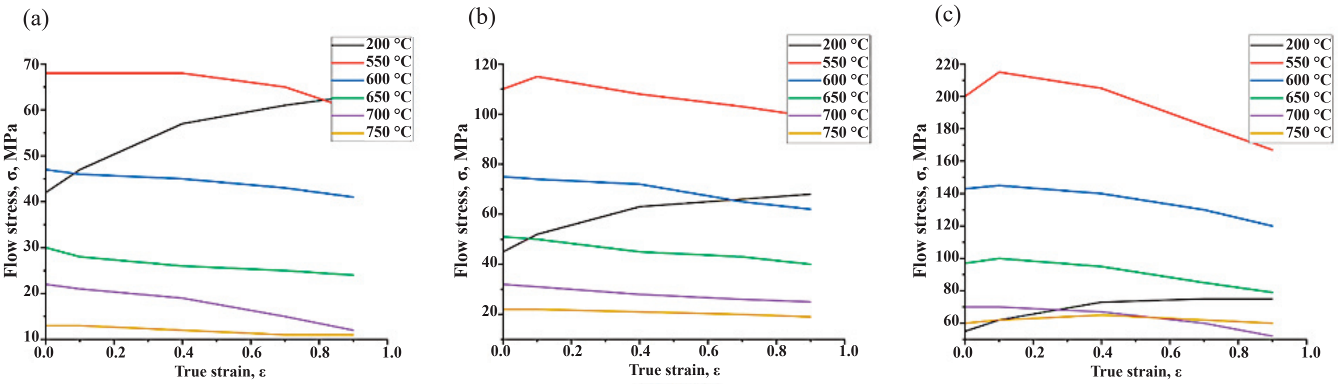

Fig. 3. Hot working strain curves at different temperatures and strain rates of 0.1 s^{-1} (a), 3 s^{-1} (b) and 100 s^{-1} (c).

complete, with an effective stress of 12 MPa and the die retracting. The valve cover rim thins with deformation, resulting in a lower stress of 7.2 MPa in this region.

The hot deformation process is highly influenced by the forging temperature, particularly with respect to the metal flow behavior. As shown in Fig. 4, the effective stress distribution in the deformed billet is non-uniform, with the regions of lower strains exhibiting the highest levels of effective stress. 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 was initially associated with low effective stress regions (blue-colored areas in Fig. 5), based on the hypothesis that insufficient billet heating leads to localized material sticking, reducing material flow and resulting in lower stress development. However, the apparent randomness in the color distribution of these plots suggested potential mesh-related artifacts. To validate this, the simulation was repeated using a finer mesh. The refined results produced smoother and more consistent stress distributions, eliminating the noise observed in the initial plots. This confirmed that the low-stress regions are localized due to temperature variations and uneven contact pressure between the billet and the die, rather than random artifacts. The updated figures, included in the revised manuscript, demonstrate these improvements and reinforce the hypothesis that insufficient heating can contribute to localized die adhesion.

Flow stress exhibits an inverse relationship with forging temperature such that an increase in temperature results in a decrease in flow stress at a constant strain rate and vice versa. When the deformation temperature and strain rate are held constant, the flow stress increases until it reaches a maximum value at the peak strain point. At peak strain, flow stress of a material that undergoes dynamic recovery softening stabilizes as the strain continues to increase. In material science, it has been observed that in the case of dynamic recrystallization, flow stress decreases after peak strain and eventually reaches a steady state.

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.

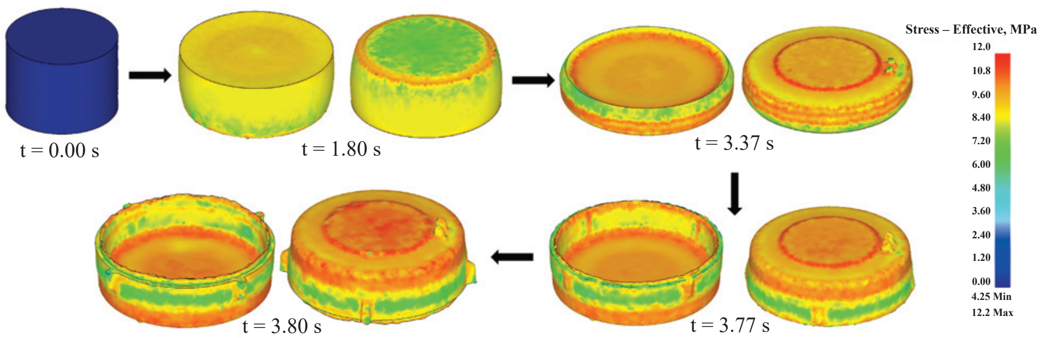

Fig. 4. Effective stress distribution at t = 0.00 s, t = 1.80 s, t = 3.37 s, t = 3.77 s, t = 3.80 s.

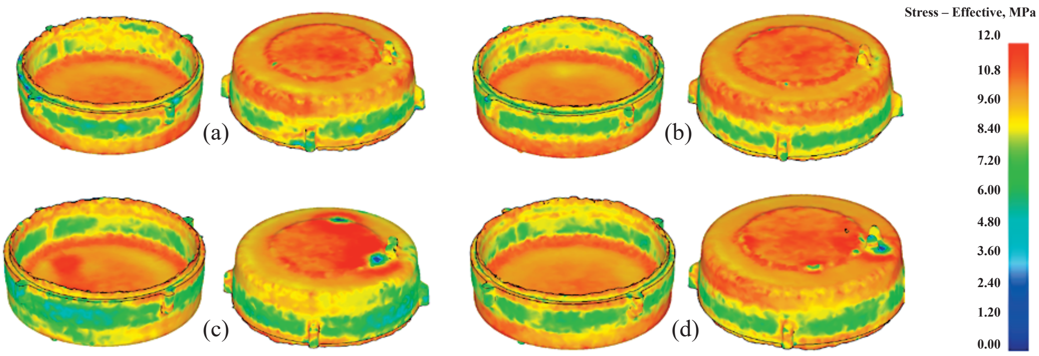

Fig. 5. Effective stress distribution at different billet temperatures with constant die temperature (350 °C): billet temperature 750 °C (a), billet temperature 700 °C (b), billet temperature 650 °C (c), billet temperature 600 °C (d).

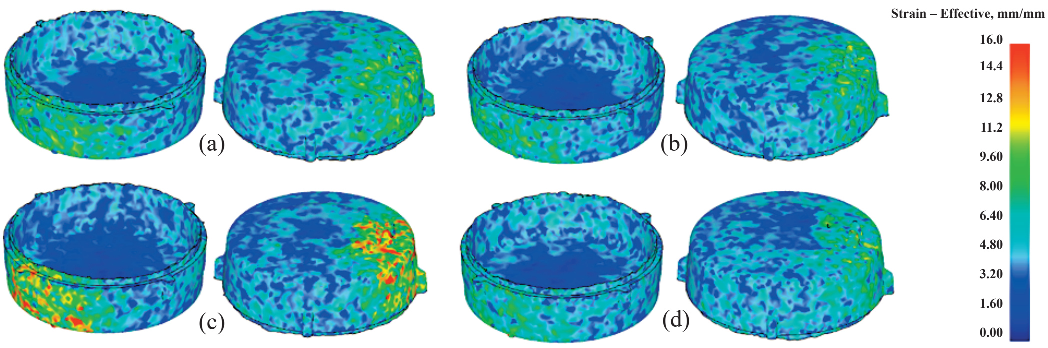

Fig. 6. Effective strain distribution at different billet temperatures with constant die temperature (350 °C): billet temperature 750 °C (a), billet temperature 700 °C (b), billet temperature 650 °C (c), billet temperature 600 °C (d).

5. Conclusions

The DEFORM 3D finite element method simulation code was developed to analyze the closed-die hot forging process of the water valve cover, which was originally a cylindrical billet. The simulation analysis compared stress and strain values across a forging temperature range of 600 °C to 750 °C, with a 50 °C increment and a strain rate of 1 s^{-1}. The study produced the following observations:

- The hot forging process results in non-uniform deformation of the billet, with the central region experiencing concentrated effective strain. The stress and strain distribution in the forging process reflects the complex interplay of material flow, die geometry, and thermal gradients. While regions with reduced strain often exhibit higher effective stress due to constrained material flow, this is not universally the case. In this study, the central region of the part, which showed the lowest strain levels, did not correspond to the highest stress levels. Instead, the highest stress levels were observed near the die-contacted regions, where significant deformation occurred. This observation highlights the influence of localized contact conditions and temperature gradients on stress accumulation during forging. The variability observed in the standard deviation provides additional evidence of non-uniformity in the forging process.

- The study demonstrated a direct relationship between forging temperature and metal particle flow rate. Specifically, increasing the forging temperature was found to increase the metal particle flow rate correspondingly. This observation suggests that higher forging temperatures reduce resistance to deformation. Accordingly, the findings are consistent with the actual industrial forging process, indicating that computer simulation can provide a reliable solution for predicting the flow behavior of the metal billet during the forging process.

Data availability statement

All data are available in the article.

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Lõplike elementide simulatsioonimudel defektide uurimiseks CuZn40Pb2 messingisulamist veeventiili katetes kuumsepistamise protsessis

Mehmet Ceviz ja Isik Cetintav

Töös uuriti CuZn40Pb2 messingisulamist veeventiili katte suletud stantsiga kuumsepistamist, kasutades traditsioonilist ühetaktilist sepistamispressi. Peamised tegurid, mis mõjutavad defektide teket materjali geomeetrias, on silindrilise tooriku geomeetria ja stantsi temperatuur. Materjali voolukäitumisele avalduva temperatuuri mõju optimeerimiseks töötati välja lõplike elementide mudel (LEM), kasutades rakendustarkvara Deform® 3D. Simulatsioonimudelites võeti sisenditena arvesse geomeetriat, täitmise järjekorda ja rakendatud jõudu. Eksperimentaalsed katsed näitasid, et hõõrdetegur, mis on määrdeainete kasutamise korral väiksem, mõjutab oluliselt materjali voolamist, kuna sepistamise ajal kuumutab hõõrdejõud stantse, mis omakorda vähendab hõõrdetegurit ja võib suurendada defektide tekke tõenäosust. Simulatsioonidest saadud pingete ja deformatsioonide analüüs näitas keerulist seost temperatuuri ja hõõrdeteguri vahel, mis mõjutab defektide teket. Läbiviidud simulatsioonid olid kooskõlas eksperimentaalsete tulemustega, kinnitades numbrilise modelleerimise sobivust defektide prognoosimiseks ja vähendamiseks. Uuring pakub väärtuslikku teavet CuZn40Pb2 messingisulamist veeventiili katte suletud stantsiga kuumsepistamise kohta, rõhutades temperatuuri ja hõõrdumise kontrollimise olulisust. Töö tulemusi saab kasutada sepistusprotsessi projekteerimiseks ja töö optimeerimiseks, et toota kvaliteetseid tooteid.