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ANALYSIS OF THE PREFORMING STAGE IN THE CLOSED-DIE HOT FORGING PROCESS

Mihajlo MILOJKOVIĆ[1]*, Saša S. RANĐELOVIĆ[1]
Orcid: 0000-0002-2334-8929
[1]Faculty of Mechanical Engineering, University of Niš, Serbia
*Corresponding author: mihajlomilojkovicwp.4@gmail.com

Abstract: *Closed die hot forging is the most frequently used forging method for industrial manufacturing of complex parts. When it comes to complex parts, an optimised preforming stage is crucial to achieve for precise finished products. Because it is consisted of multiple sequences, there is significant room for enhancement and innovation in industry settings. This article goes through multiple advanced ideas and papers that tackle this problem and analyses their further implementation in conventional settings. Additionally, it examines the optimisation of preforming on an industry case study with a specific product and reviews the future scope of implementing new-age methods for easier and precise optimisation.*

Keywords: *Closed-die hot forging, preforming, billet, optimisation, industrial case study, experimental study, multi-stage hot forging.*

1. INTRODUCTION

Forging refers to the method by which metal undergoes plastic deformation through the application of heat and pressure. The process can be performed at various temperatures, leading to different types of forging: cold, warm and hot forging. For future referencing, in this article the main type of forging that will be discussed is hot forging. Hot forging includes shaping metal at raised temperatures, usually between 700°C and 1,200°C. The metal is heated to provide flexibility and make it more pliable. Components produced through the forging process, referred to as "forgings," exhibit enhanced structural integrity, impact strength, fracture toughness, fatigue endurance and uniformity, with very high dimensional accuracy. The significant versatility of this process is evident in its ability to produce forgings from a wide range of metal materials, including steel, aluminium, titanium, and various alloys, in nearly any size and shape. A forging process is considered successful when the die cavity is entirely filled and the stress within the workpiece remains below the ultimate stress associated with the material of the workpiece, all while utilising the least amount of force. Finite Element (FE) simulations are frequently used in the design of forging sequences, as they serve as an excellent resource for identifying and evaluating quality parameters such as form filling, folds, forming forces, and temperature profiles. Complex geometries in forgings are created through multi-stage processes. In these instances, it is crucial to identify the optimal design for the multi-stage process that minimises the number of forging steps.

1.1. CLOSED-DIE FORGING

In closed die forging, often referred to as impression die forging, the die exerts pressure on the material via the interface, leading to the formation of a cavity shaped component. A standard configuration of closed die forging is illustrated in Figure 1.

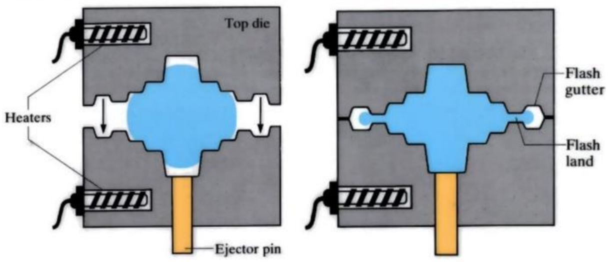

Figure 1. Schematic arrangement of the closed die hot forging process

The parameters for input and output, as well as their interconnections, must be examined in relation to their impact on product quality to enhance process efficiency.

1.2. Multi-stage CDHF

Practical industrial forging typically includes several stages. The quantity of these stages is determined by the complexity of the geometry, the characteristics of the metal flow and the desired precision of the component. These stages can be divided into three main categories that differ in design and complexity, but all play an important role in the process's success and the quality of the final product.

- Upsetting
- Preforming
- Finishing

These stages can consist of multiple sequences. A categorized view of a full forging cycle including these stages is displayed in Figure 2 [1].

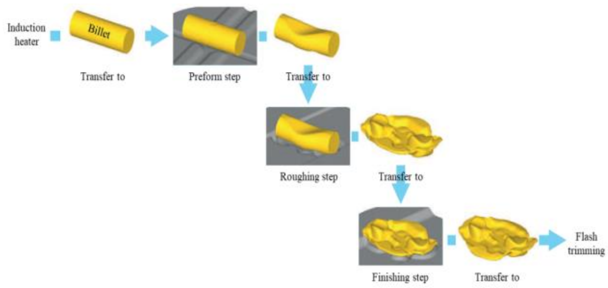

Figure 2. Forming stages in the hot forging process

2. OPTIMISATION METHODS

As previously mentioned, the upsetting and preforming steps in CDHF are crucial for achieving and maximising the efficiency of total die coverage during forging. The upsetting is typically planned and developed by forging engineers, relying primarily on their experience and iterative trial-and-error design process. In industrial practice, once engineers receive the necessary product documentation, the design process begins with drafting the billet's shape and dimensions in relation to the final product, taking into account its overall geometry, volume, and mass. Next in line is a series of tests to see if some changes to the initial values of the billet improve the process parameters and optimise it. Finally, the definitive billet parameters are adopted and the process goes into its ensuing stages. Some articles tackle this initial process with the help of optimising software and FEM analysis and will be discussed in the upcoming subsections.

2.1. Different billet optimisation methods

Mangshetty et al. [2] applied FEM in ANSYS, coupled with optimisation algorithms, to analyse how billet height-to-diameter ratios affect metal flow, strain distribution, and die loading in aluminium MMCs. Their results showed that optimised ratios could reduce forging loads by nearly 10 kN, however the framework was limited to a 2D simulation with simplified frictional and thermal conditions, excluding aspects such as die life or multi-stage sequences. Soranansri et al. [1]

extended billet optimisation into a full process design by combining billet geometry selection with hot forging die design and experimental validation for biomedical prostheses. Their study confirmed that billet geometry of Ø36 × 99 mm improved material utilisation by over 260% and ensured defect-free die filling, with the mass ratio factor identified as a key sizing parameter, although the work was restricted to AISI 316L and did not assess scalability or die wear. Han et al. [3] introduced a data-driven methodology by generating NURBS-based preform geometries and training CNNs on FEM-derived microstructural data, achieving up to 19.64% grain size refinement and 40% load reduction in IN718 forging. Despite these advances, the approach relied on computationally expensive datasets, image-based CNN training with limited interpretability, and validation only on a single superalloy. Collectively, these works demonstrate that billet optimisation through FEM, experimental validation, and machine learning can improve forging efficiency and accuracy, but they remain highly material-specific and computationally demanding, limiting their broader industrial implementation.

2.2. Preforming optimisation

Claus et al. [4] proposed an automated forging sequence design method integrating ANN-based shape classification, a complexity scoring model, fuzzy logic for stage determination, and a point-shift algorithm to generate preforms directly from STL geometries. FEM simulations verified that the approach could provide viable forging sequences with satisfactory filling in under one hour, but the outputs were only approximate, misclassifications occurred, and crucial geometric features like draft angles and fillets were excluded. Aybar et al. [5] analysed four forging process routes for a torque rod housing using FEM and experimental validation, demonstrating that preforming stages (including upsetting and shaft crushing) were essential to achieve full die filling, minimise burr formation, and halve die stresses compared to single-step forging. However, their reliance on conventional volumetric distribution graphs restricted the designs sophistication and applicability. Huang et al. [6] conducted a multi-objective optimisation of preforming dies for I-shaped forgings with DEFORM-2D, comparing linear and arc-shaped transitions between web and wing. They found that a linear angle of 53.5° and arc radius of 66 mm reduced loads by up to 76% and improved wear distribution, although the use of 2D models and simplified design variables limited industrial use. Movrin et al. [7] applied the finite volume method to optimise wheel hubs and sockets, testing process variants to balance die filling, contact pressure, and stage reduction. Their optimised approach achieved pressures below 1100 MPa and defect-free production trials, although the simulations used simple friction and heat transfer assumptions and overlooked long-term tool fatigue. Taken together, these studies illustrate how AI-based automation, FE modelling, and experimental validation converge to show that preforming remains very important for reducing forging loads, ensuring material flow, and extending die life. However, for robust industrial adoption, progress is required in realistic thermo-mechanical modelling and wider material coverage.

3. INDUSTRY CASE STUDY

This paper has, to this point, presented the basics of forging and intricacies of closed die hot forging. A number of articles were covered that show the importance of billet shape/dimension and preforming design optimisation. The integral nature of preforming in a multi-stage process will be presented with a industrial case study. The study is based on the forging process optimisation of a drawhook that is used in the railway industry. The hook is made in the ˝Ming˝ production plant [8], which is specialised in machining and forging. In Figure 3 the hooks dimensions are presented.

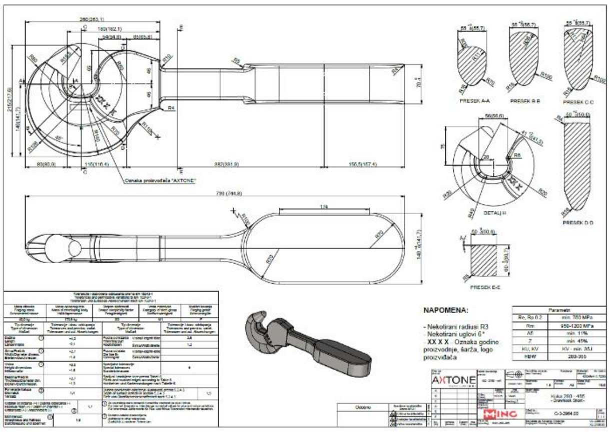

Figure 3. Drawhook technical drawing

From the shape of the hook it can be assumed that the preforming stage will be complex, because optimal mass redistribution cannot be achieved with one step of preforming. The mass of the hook is 41kg. In an industrial setting the flow of the whole forging process is mainly dictated by engineering experience and trial by error design. Firstly, the mass of the finished product is increased by 20% - an optimal initial increase that accounts for the mass that is lost in the flash of the forging and also in the trimming process after forging. This percentual increase is obtained through experience. By analysing the shape of the hook it is determined that the optimal shape of the billet is cylindrical. From the dimensions of the hook, the presumed length of the cylindrical billet is 505 mm and it will later be tested and optimised. In corelation to the length, the presumed diameter of the billet is 110 mm. After establishing the initial dimensions of the billet, initial testing of the billet is required to examine if it meets dimensional requirements.

The FEM analysis is done in the FORGE programme developed by Transvalor. The initial idea is that for this forging process two preforming steps are required with one finishing step. Preforming is conducted using a basic upsetting die on different parts of the cylinder. The first step of preforming is presented in Figure 4.

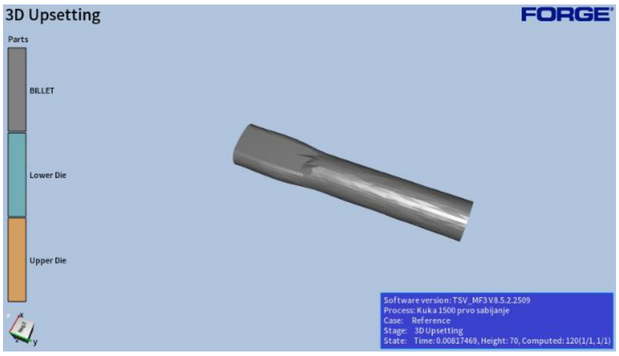

Figure 4. The first step of preforming – free upsetting on one end of the cylinder

The next step of preforming is done in a similar fashion to the first, but in a different plane to secure the complex geometry and shape on opposite ends of the hook. The second preforming step is provided on Figure 5.

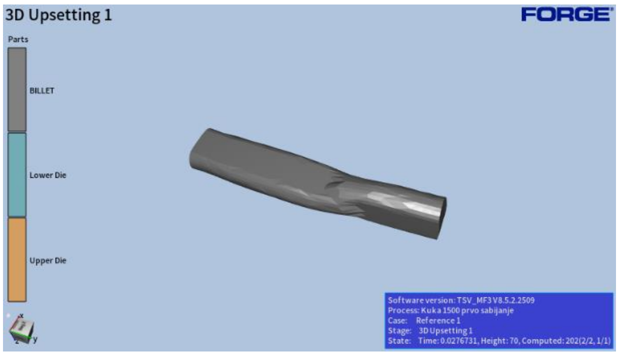

Figure 5. Second preforming step – flattening of the cylinder in a different plane

The finishing step of forming is done in a specially designed die made using a numerical mill. Bottom and top dies are presented in Fig. 6 and 7.

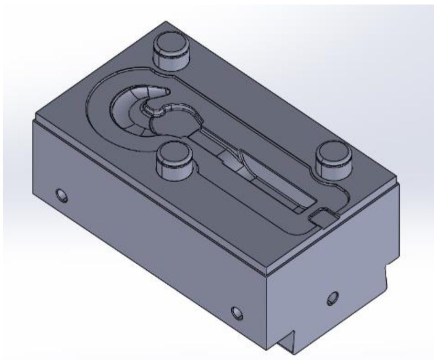

Figure 6. Bottom die design in SolidWorks

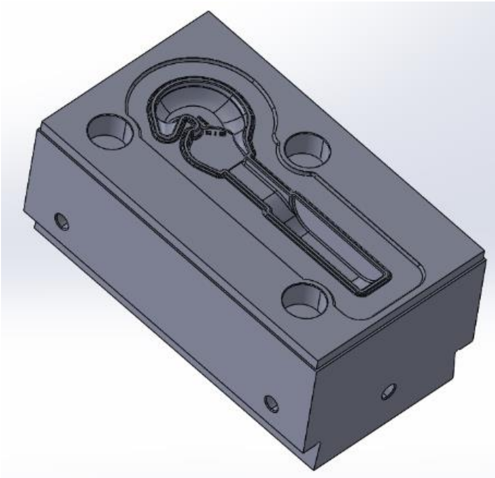

Figure 7. Top die design in SolidWorks

After the simulation of the finishing step, it is concluded that the die filling is not optimal. Finishing geometry is not ensured because the mass redistribution is not properly achieved in the preforming stage. Because of the underfill, the rounded edges are not made and also there are surface impurities. The finished part after the finishing stage is shown in Figure 8.

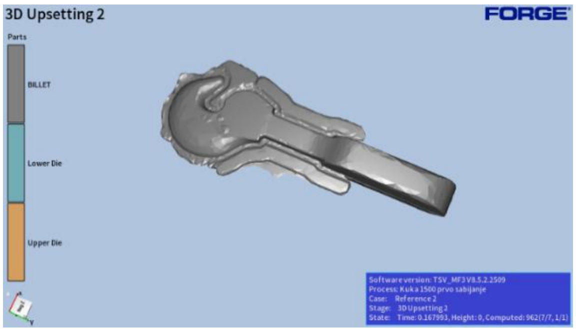

Figure 8. Finished part after the finishing step

Even though the forging is not optimal, the process is verified in industrial conditions to determine validity of the FEM simulation and results. Simulation results and results of the industrial trial is compatible. Compatibility insures that, after the process is optimised in the simulator, changes are applicable in real life.

The first changes to the process are started with the billet. The length is shortened to 490 mm and the diameter is increased to 120 mm. This change is determined by engineering experience. Preforming is more complex, with 5 preforming steps to ensure the most optimal mass redistribution and later on metal flow. Preforming is also done by free upsetting different areas of the cylindrical billet. This change in the number of steps is based on trial and error and by watching different parts of the hook in different planes. The optimised version of preforming is shown in Figure 9.

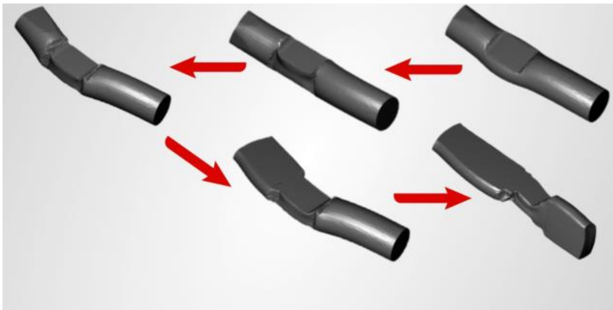

Figure 9. The five steps of preforming

From the pictures of the optimised preforming stage, it can be determined that the new preform more closely resembles the finished part, so the final dimensions and tolerances are easily made in the finishing step. The first preforming concept is more simple and was the first trial because it is more economically justified, but because the process is not optimal the second preforming version is the only applicable version. The finishing step is presented in Figure 10.

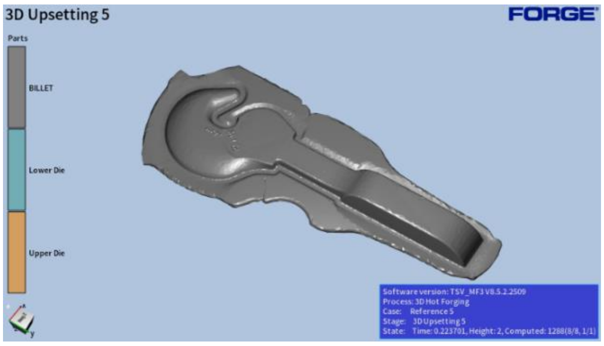

Figure 10. The finishing step of forging

When the finishing stages of the two concepts are compared, there is a major difference in flash formation, the dimensional tolerances are justified and rounded edges and angles are obtained.

The final process parameters are:

- Temperature of 200 °C on the bottom and top dies
- Force of the die is 160 kJ
- Including preforming and finishing stages – 10 steps of the process

- Temperature of the billet is 1050 °C
- Material of the billet is 42CrMo4

After the forging process, the forged hook is trimmed and the flash is removed. In industrial settings, problems that are being faced in forging products are resolved mostly like the sequence that was presented here. Because of the volume of demand for forged parts at industrial plants like ,,Ming˝, this is still the main way and frequently the most effective way of tackling these problems.

4. CONCLUSION

Using the industry case study as an overview of the workflow that is usually applied in industrial settings, it can be concluded that there is much room for optimisation. Some of the presented algorithms and neural networks/machine learning ideas for optimisation can be utilised and implemented on the industrial level, making the trial and error method and optimisation based on experience obsolete. The sheer volume of production at plants complicates the implementation of these ideas and methods, but these ideas are the future of optimised and efficient forging. Plants that have big databases of production parts, faced problems and their solutions are the perfect starting place for developing and broadening these algorithms/networks. Future work will focus on implementing these ideas in a product of industrial plants.

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