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ORIGINAL ARTICLE

Preform geometry determination for a connecting rod forging by CEL model in Abaqus™

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Abstract

Forging is a widely used manufacturing process, and its design and modeling are important to reducing production costs, increasing die lifespan, and improving the mechanical properties of the final product. In this study, the forging process of a connecting rod was modeled using 3D coupled Eulerian Lagrangian (CEL) analysis by FEM. The methodology adopted achieved to determine a preform geometry that reduces final flash and forging load, while ensuring complete filling of the stamp. Starting from the final geometry, the final die was designed. After the first result for an approximately 27% of flash, the material distribution was adjusted decreasing it at the regions where the flash was too large. After an iterative method was applied to determine better preform, a proposal was found that reduced forging force by approximately 42% and the percentage of flash volume by 64% in comparison with the first one. A final flash of about 10% is considered a good objective to reach. Lower values may cause many iterations, not a significant difference in forging loads, the risk of an unfilled die, and complex preform geometries.

Keywords Forging process · Preform design · Finite element modeling · CEL analysis · Connecting rod

1 Introduction

The forging process provides numerous advantages over other manufacturing methods such as the ability to forge most materials, few restrictions on the size of the pieces, achieving good tolerances and high strength, while keeping low production costs for high volumes. FEM modeling of the forging process is a valuable tool for predicting material flow, die and product stress levels, possible defects, to calculate the forging force, helping to optimize the process, and reducing losses and costs.

Two methodologies are used in the design and manufacture of die forging: one designed by CAE (computer-aided engineering) and the other using empirical rules. A good design implies the use of both methods. During the preform design, the proper distribution of the material and flow free of defects must be established, ensuring the correct filling of the stamp, minimizing flash and die wear.

Deformation patterns may require several steps, making the preform design a complex process that typically relies on empirical information based on experience. The flow is influenced by the complexity of the die; then, the necessity of preforms in a forging process depends on that.

Valberg shows possible forging sequences for cross sections *H* based on the relationship between *h* and *b* rib dimensions [1]. Other researchers have proposed more general classifications to estimate costs and to predict preforms based on experience. Domblesky et al. suggest that a preform is needed based on Spies classification of forging parts [2], and Tomov and Radev presented a classification for axis-symmetrical hot die forgings [3].

Dies with complex shapes, small fillet radii, and thin sections pose challenges in the forming process. To apply computational methods, a relationship between the final and the initial geometry needs to be defined. Tomov´s approach assumes that the work done can be calculated when an arbitrary component is forged. They propose an equation that establishes a relationship between the amount of work done by extrusion and the need for an intermediate stage [4].

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Blockers are preforming operations done just before the finishing die. They give the workpiece its final general shape, omitting fine details by moving the material through generous fillets. Prior to blocking die, the material is redistributed by roller or open forging to regions that will be needed in later stages. It is common to manufacture the blocking die by duplicating the finishing die and then rounding it for smooth flow. However, a better approach is to make it slightly narrower and deeper than finishing stamp. Choi provided qualitative recommendations for the blocking die and other aspects of the forging process [5].

Designing the finishing die involves the use of several rules, empirical equations, and tables to guide the designer in obtaining an adequate final stamp, but not optimized. It is common to start from the final machined piece; thus, it is important to consider the amount of material that will be removed in the final finishing stages where surface defects are eliminated.

The first step is to over-thicken the geometry [6, 7], using a surface partition line, weight, or the different dimensions of the piece. Fillets and exit angles must also be considered [8]. Finally, the flash cavity must be designed using expressions and tables to determine the appropriate dimensions [9–11]

Various methods have been proposed by different authors to optimize preforms. Oh and Yoon focused on the design of the blocking die for an axisymmetric rib-shaped part using different approaches. They found that blocker geometry can be generated by filtering out high-frequency modes from the finished geometry, outlining a process that converts the finished die into a preform using low-pass filters [12].

Forging preform design affects material flow, forming load, accuracy, and tool wear. Ngo et al. conducted a study using evolutionary structural optimization to obtain optimized preforms. The objective was to obtain the best preform that ensures complete filling with minimal material usage. In comparison with Tang et al. [13] proposal, it was observed that the first one offers a simpler form, with both achieving complete filling [14]. Fourment et al. also analyzed the preform design as an optimization problem, defining an objective function and calculating gradients based on preform geometry using an algorithm. The study focused on an axisymmetric rib geometry, obtaining an appropriate preform after several iterations [15].

Forward and backward simulations of the forging process based on rigid viscoplastic methods can provide a preform shape from the final part to be forged. To reduce flash, Zhao et al. used a finite element model considering plane deformation, based on an inverse method of contact tracing to design the preform. To establish the material requirements, the material flow and die filling were analyzed. They found that the location of the workpiece in the cavity die was a critical factor in achieving the appropriate volume distribution [16]. Similarly, Hawryluk and Jakubik found that proper spacing of the cross section along the length of the main axis of the preform is important for filling the die cavity, resulting in a 10% reduction of the billet volume [17].

Di Lorenzo and Micari presented an inverse approximation method to optimize the preform geometry by evaluating the response function, which links the set of parameters defining the preform. Their study showed that additional 5% volume of the total part is necessary to complete the cavity filling [18]. Vazquez and Altan conducted research on designing a flash-free preform for a connecting rod and introduced a concept for complex forgings with a controlled amount of flash. They found a good approximation for 18% of flash while for 5% of flash resulted in unfilled die cavity [19].

Park and Huang developed a finite element model of rib-shaped components. They proposed a systematic approach to preform design, consisting of three steps. Firstly, they selected several cross sections that represent the critical flow zones and simulated them in 2D. Secondly, based on the results of the first step, they designed a simple preform shape and evaluated it in 3D. Finally, they analyzed volume redistribution based on the second step to eliminate unnecessary material flows [20].

An algorithm for the practical designation of preforms for complex parts is proposed by Sedighi and Tokmechi. In many cases, the final preform proposal has unconventional shapes which make them difficult to manufacture. The algorithm has two stages; in the first stage, a preliminary preform is considered that fills the cavity. In a second stage, the preform is improved using a control criterion. They obtained an optimized preform without defects [21].

Fuertes et al. presented the design, model, and experimentation of forging process, using an iterative approach. The first billet and die were designed based on basic principles. They then analyzed material flow and die filling using finite volume simulations. Based on the simulation results, they adjusted the material distribution by increasing it in areas that the cavity was not filled and decreasing it if the flash is too large [22].

Kim and Kim developed a program based on UBET (upper bound elemental technique) to analyze the forging process in a closed die. They also proposed a new procedure for designing preforms that includes a backward tracking scheme and a criterion for controlling boundary conditions. By comparing simulation results with experimental data, they obtained a good approximation of the forging loads and material flow behavior [23]. Takemasu et al. optimized the preform for a flashless connecting rod. They obtained the volumetric distribution by cutting cross sections, and the die was generated based on those. The preform was divided into three regions: head, connector, and small end, obtaining different proposals for each region [24].

After this review, it was shown that several studies analyze the parts using 2D or axisymmetric models or by eliminating details of the final 3D geometry. In this study was followed a methodology to determine the preform geometry that decreases the final flash, reduces the forging load, and ensures the filling of the stamp during the forging process of a connecting rod. The proposal utilizes a 3D model and CEL method in Abaqus™, eliminating the need for remeshing operations typically required in traditional Lagrangian method [25].

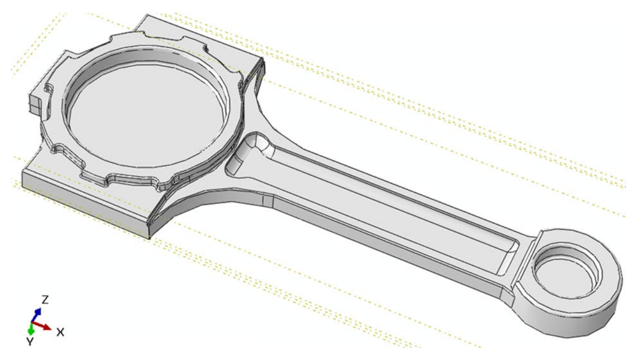

Fig. 2 Half symmetry forgeable connecting rod

2 Modeling methodology

The methodology proposed starts with the final piece geometry; in the present study case, a commercial connecting rod shown in Fig. 1 was used.

It was necessary to modify the drawing of the connecting rod to design its forging die. The first modification was to eliminate regions that could not be created by the natural movement of the dies and to establish the partition line considering the piece symmetry. Then, the tolerances for impression die were calculated, considering the methodology proposed by the Forging Industry Association [7]. Tolerances between 1.1 and 1.4 mm were obtained depending on the dimension.

Subsequently based on García's work [8], the exit angles and the radii on the edges were calculated to ease piece extraction and favor the material flow. Connecting rod has two through holes that normally cannot be achieved by forging; however, they can be considered as blind holes, so the thickness of the core was determined [5]. Figure 2 shows the modified geometry taking into account previous considerations.

The flash cavity parameters were calculated, aiming to obtain approximately 10% of the total part volume as flash. This was done using classical tables, relationships, and equations presented by Del Río [11]. The resulting finishing die is presented in Fig. 3.

Having the finishing forging die, a first preform proposal geometry was considered with a volume equal to the final forged part plus an additional 25%, to ensure stamp filling and achieve the desired 10% flash after optimization.

The connecting rod was initially divided into three regions: head, connector, and small end, and the volume of each one was obtained from the CAD model. Then, approximately 25% of the volume of each region was added to create the preform. The head and small end regions were given the same height, 15% greater than the highest dimension of the part in those regions, to promote compressive flux accordingly to basic recommendations. Both regions were modeled as cylindrical with circular areas to obtain the calculated volume. For the connector region, it was applied the same methodology to obtain the height, and a rectangular prism was created with a length of 10 cm. Finally, fillets of 6.4 mm were added to the transition regions. First preform proposal is shown in Fig. 4.

A coupled Eularian-Lagrangian (CEL) approach was chosen for the process modeling due to its advantages over a

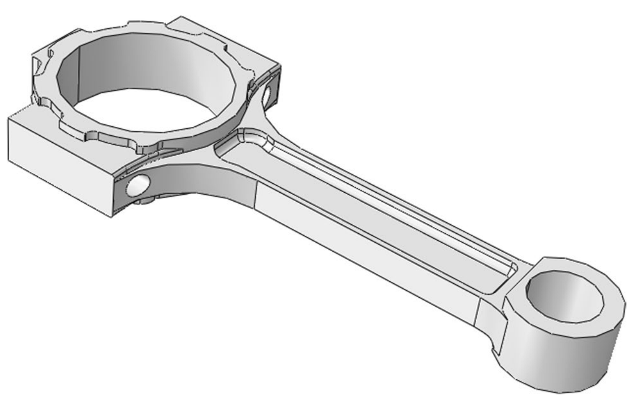
Fig. 1 Final piece geometry

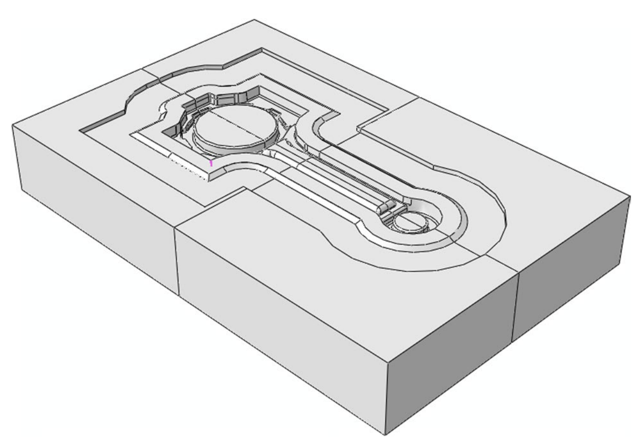
Fig. 3 Connecting rod finishing forging die

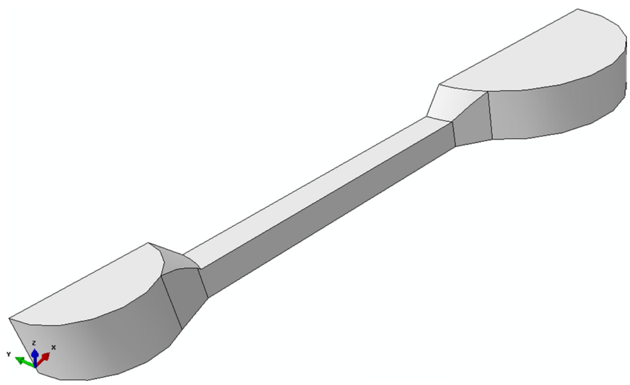

Fig. 4 One-fourth symmetry preform

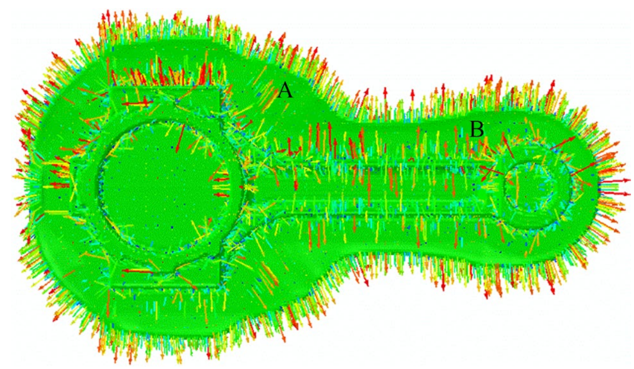

Fig. 5 Vectorial representation of displacement for the first preform

Table 1 Stress–strain curve data [26]

σ (MPa)	ε
40	0
90	0.1
110	0.2
120	0.3
125	0.4
125	0.5
120	0.6
115	0.7

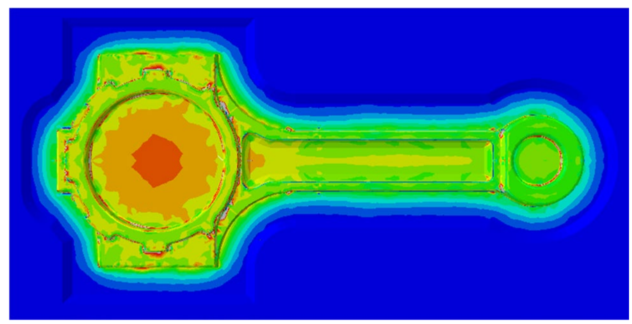

Fig. 6 Contact pressure showing contact regions between die and forged preform 1

purely Lagrangian approach, which would require additional effort to control mesh distortion. The model was assumed to be isothermal.

The die was considered as rigid, the preforms as deformable with mechanical properties of a 0.35% C steel. Additionally, since it is a Eulerian model, the region known as domain was created spanning all the regions where the material can flow. As general material properties, a density of 7870 kg/m^3, Young's modulus of 206 GPa, and a Poisson ratio of 0.29 were used. For plasticity, stress–strain curve data at 1100 °C and 20 s^{-1} were used (Table 1) [26].

An explicit dynamic step was considered, and a time of 0.051 s was selected based on a speed of 254 mm/s for the upper die [16]. For contact conditions, it was used a 0.3 friction coefficient [27]. The domain mesh had 303,552 Eulerian elements (EC3D8R) of 1-mm size, and the die had a 12,121 elements of discrete rigid type.

3 Results and discussion

For the first preform, the flow was radial at the head and small end of connecting rod and lateral at the connector region, similar to plane strain conditions. This resulted on a homogeneous flash length distributed around the piece, with a slight increase of flash length at the head-connector and connector-small end interfaces, shown in zones A and B, indicated in Fig. 5. This pointed out to a proportional decrease for each region as a good alternative for a second proposal.

In addition, the contact pressure at the die was used as an additional result to analyze the stamp filling, along with visual analysis of the model. Forged preform 1 exhibits contact in all surfaces of the stamp (Fig. 6), indicating that the filling was guaranteed.

From forged preform results, the material distribution was adjusted by decreasing it at the regions where the flash was too large. Then, 5 different numerical models were developed to reduce the flash by changing the preform geometry and dimensions. For a second perform, the flash was reduced to approximately 10% of the part volume following a similar methodology to the first preform.

Visually, the second preform shows that the die was filled, but in the contact pressure, presented in Fig. 7, there is an area at small end that looks unfilled. As a result, a third preform proposal was made, increasing the head and small end radii, and maintaining the connector dimensions of the second preform.

Therefore, the filling of the third preform was guaranteed without a significant increase in volume and forging force

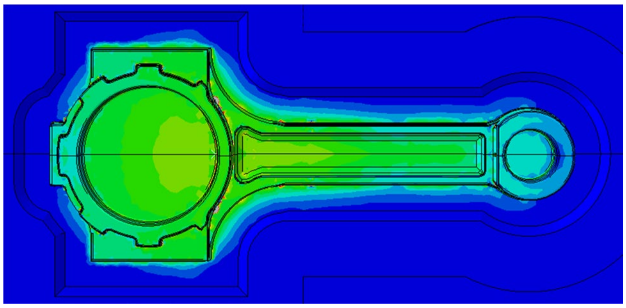

Fig. 7 Contact pressure showing contact regions between die and preform 2

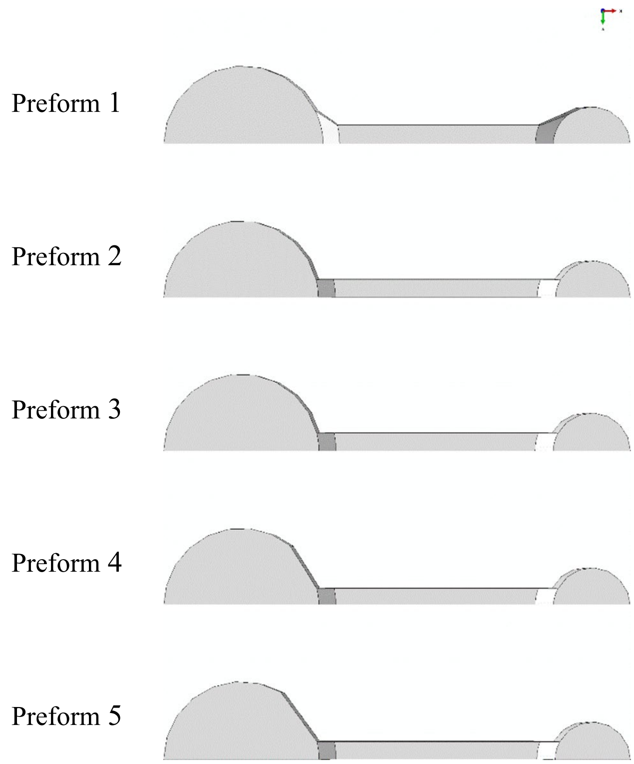

Fig. 8 Preform geometry evolution

compared to the second preform. Subsequently, a fourth proposal was made seeking to reduce the flash volume percentage by focusing on the region between head connector of the preform, where the amount of flash was greater in the three previous models. Preform 3 was cut, decreasing its volume by 0.7 cm^3.

The results for the fourth proposal were a complete filling of the stamp, reducing flash volume percentage and forging load compared to preform 3. In addition, it showed a homogeneous distribution of contact pressure on the stamp, which was considered as a good result. However, as an additional analysis looking for a 10% of flash volume, a fifth proposal was made based on preform 4, where the width of the preform connector and the small end diameter were reduced.

Preform geometry evolution is presented in Fig. 8; dimensional changes mainly obey to flash reduction. However, during the first model solution, it was observed that flash geometry was excessive at transition regions between head-connector and small end-connector; hence, a geometry modification was required as can be observed between preforms 1 and 2. For preform 3, a dimensional adjustment was applied, and for preform 4, a second geometry modification was considered. Finally, for preform 5 small adjustments were done.

Figure 9 superimposes the top views of preforms 1 and 5 before (a) and after forging process (b), where the difference in the amount of flash becomes evident. Geometry changes proposed for final model 5 do not increase the preform complexity but reduce considerably flash and material volume.

After obtaining the preform, the manufacturing process is shown in Fig. 10. For this model, a lateral and an upper die were used. However, due to the preform's simple geometry, the same result could be achieved through drawing and edging operations and the final preform shape could be obtained by a fullering operation or forging with rollers.

To compare the FEM model results, the forging force was calculated, considering it as a complex shape with flash, then $C1 = 8$ [28]; subsequently, the projected area including the flash was determined. If the half surface of the part is 87 cm^2 and the approximate flash area resulting from the first simulation was 99.4 cm^2, the total area was 186.4 cm^2. Considering a stress of 115 MPa, accordingly to Messner et al. [26], at the highest strain, $F = 8\ (18{,}640\ mm^2)\ (115) = 17.15$ MN, which differs 1.35 MN from the 18.5 MN obtained as maximum force in the simulation of the first forged preform.

Calculated forces determined for different models' results are presented on Table 2; it can be observed that model 1 exhibits the highest flash volume percentage, and the model 5 the lowest value. Model 2 did not fill the die form, but it was corrected for model 3. Models 4 and 5 achieved a decrease in material and presented a flash volume percentage

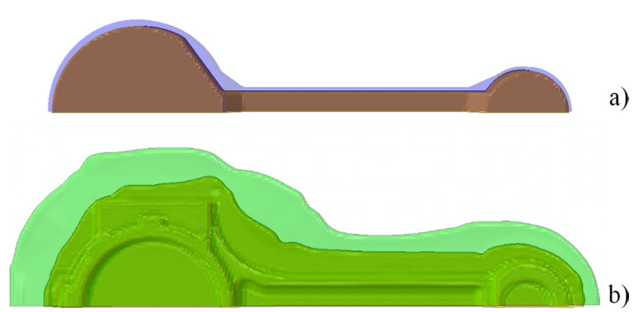

Fig. 9 **a** Superimposed preforms (model 1 (blue) and model 5 (orange)). **b** Final forged geometry (model 1 (green) and model 5 (orange))

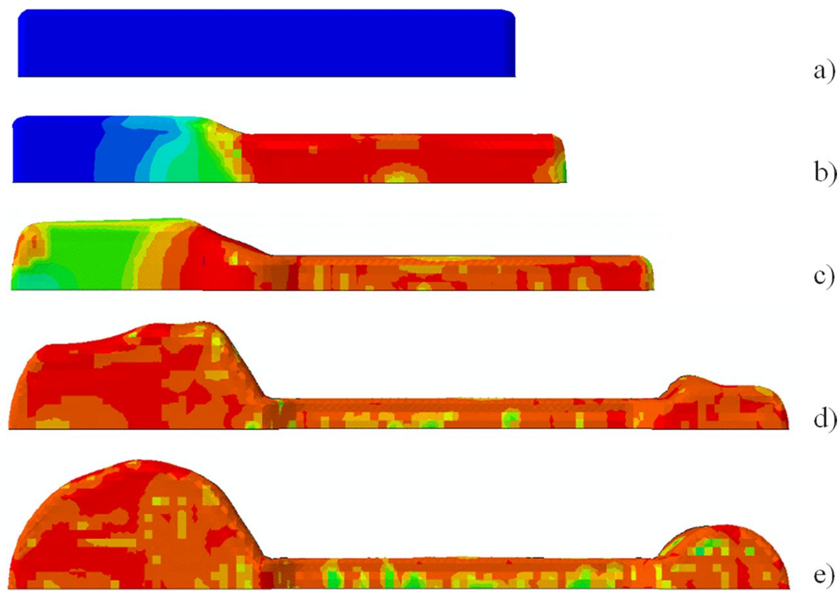

Fig. 10 One-fourth preform geometry fabrication: **a** initial slab 16×16×119 mm, **b**, **c** drawing operations, and **d**, **e** Fullering sequence

Table 2 Calculated forces for each preform

Model	Half symmetry preform volume (cm^3)	Flash volume percentage (%)	*F*max (Abaqus) (MN)	*F*max (empiric eq.) (MN)	% Error	Die filling
1	69.2	27.2	18.5	17.15	7.87	Filled
2	60.3	10.8	11.6	12.36	6.15	Unfilled
3	61.6	13.2	13	13.32	2.4	Filled
4	60.9	11.9	12.2	12.62	3.33	Filled
5	59.7	9.7	10.8	12.2	11.56	Filled

of 11.9 and 9.7%, respectively. Both presented a successful die filling.

The force curves shown in Fig. 11 obtained from Abaqus™ exhibit similar values from 0 to 10 mm of ram displacement which represent the material flow through main die geometry. After that, an exponential behavior, with an increase of approximately 5 times the force, was observed at the final 10% of the ram. This can be explained by the fact that, at this point, the material flow occurs mainly in the flash cavity. Preform 1 presents the highest forging force due to higher flash volume; preform 5 presents the lowest value decreasing up to 42% of forging force, which can produce an increase in die lifespan.

At the plot of maximum forging load vs % vol. of flash, it can be observed that a smaller flash results in a lower forging force. This is consistent with the fact that the main elevation of forging force occurs in the final stage of the ram. By fitting the data, the forging load required for any percentage of flash can be calculated (Fig. 12).

However, reducing the amount of flash poses a risk to the filling of the stamp, as seen in model 2. Due to the complexity of the flow, any proposal should be accompanied by a complementary analysis to ensure successful stamp filling. This was achieved in proposals 3, 4 and 5, where a gradual reduction of the flash volume led to satisfactory results.

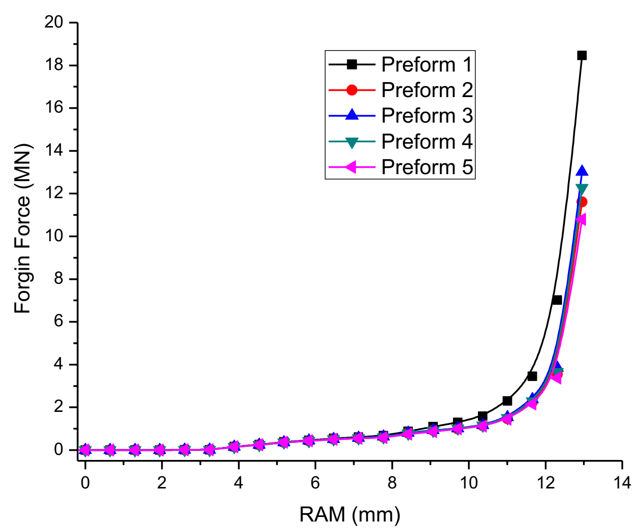

Fig. 11 Forging force vs ram for each preform

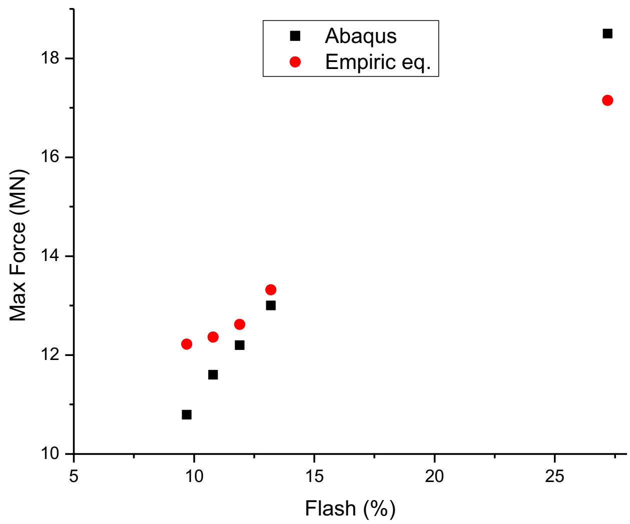

Fig. 12 Forging force vs flash %

4 Conclusions

In all the cases, an error of less than 12% was found between numerical calculations and empirical equations of forging maximum force. The result of empirical equations depends on the value used as a constant for a complex part with flash, but it proves to be a good reference for a fast calculation of forging force. If a higher value were used, the error would increase with respect to numerical models, but the obtained result guarantees that the process could be easily done.

The use of contact pressure as a result to analyze the die filling was useful because it graphically highlights unfilled regions.

To design the preform, the geometry was subdivided into regions and their volumes were determined. It was useful to have reference values for material distribution, incorporating a controlled extra volume. Following the recommendation of a geometry with greater depth than the stamp and assigning simple geometries to each region. Additionally, using FEM modeling results, it can be achieved a preform improvement by removing excess material. However, it is important to balance this improvement with avoiding unnecessary complexity in the geometry.

After the iterative method developed to establish a better preform, it was found that proposal 4 was a good result and the process could be finished there. In fact, it was the preform with the most homogeneous distribution of contact pressure at the die, which means that the filling was guaranteed, and the wear of the die would be homogeneous too.

Even with the above, it was decided to carry out one last proposal, and it was found that for the last preform, the forging force decreases by approximately 42%, and the percentage volume of flash by 64% compared to the first proposal. Therefore, an approximately 10% of flash is a good objective to reach. Lower values provoke many iterations, not a big difference in forging loads, the risk of an unfilled die, and complex preform geometries.

As further work, it is important to validate the obtained results by developing the process experimentally and measuring variables of interest such as filling and forging force. Additionally, a complementary analysis can be conducted to study overlaps resulting from the complex material flow, and it could be associated with variables in the model to enable predictions.

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Author contribution All authors contributed to the process of conception, execution, data analysis, and writing of the present work. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

References

1. Valberg H (2010) Applied metal forming, including FEM analysis. Cambridge University Press, New York
2. Domblesky J, Kraft F, Druecke B, Sims B (2005) Welded performs for forging. J Mater Process Technol 171:2
3. Tomov B, Radev R (2003) Preform design for axis-symmetrical hot die forgings. In Proceedings of the Fourth International Conference on Industrial Tools, Bled, Slovenia, Pages 175–182
4. Tomov B, Gagov V, Radev R (2004) Numerical simulations of hot die forging processes using finite element method. J Mater Process Technol 153–154:352–358. ISSN 0924-0136. https://doi.org/10.1016/j.jmatprotec.2004.04.051
5. Choi J, Kim B, Kim S (1995) Computer-aided design of blockers for rib-web type forgings. J Mater Process Technol 54(1–4):314–321. ISSN 0924-0136. https://doi.org/10.1016/0924-0136(94)01781-6
6. Bralla J (1998) Design for manufacturability handbook, Second edition, Mc Graw-Hill. ISBN 0071501789, 9780071501781
7. FIA (2022) APPENDIX A-Tolerances of impression die 9. APPENDIX A - TOLERANCES FOR IMPRESSION DIE | Forging Industry Association

8. García A (2019) Diseño de utilaje para la forja de una pieza industrial mediante simulación por elementos finitos, Grado en ingeniería en tecnología industrial. Escuela de ingeniería de Bilbao. http://hdl.handle.net/10810/36525
9. Tschaetsch H (2006) Metal forming practise. Springer, Germany
10. Tomov B, Radev R, Gagov V (2004) Influence of flash design upon process parameters of hot die forging. Journal of Materials Processing Technology 157–158:620–623. ISSN 0924-0136. https://doi.org/10.1016/j.jmatprotec.2004.07.124
11. Del Río J (1980) Deformación plástica de los materiales: La forja y la laminación en caliente. Editorial Gustavo Gili, España
12. Oh S, Yoon S (1994) A New Method to Design Blockers, CIRP Annals 43(1):245–248. ISSN 0007-8506. https://doi.org/10.1016/S0007-8506(07)62205-7
13. Tang Y, Zhou X, Chen J (2008) Preform tool shape optimization and redesign based on neural network response surface methodology. Finite Elem Anal Des 44(8):462–471. ISSN 0168-874X. https://doi.org/10.1016/j.finel.2008.01.007
14. Ngo N, Hsu Q, Li W, Huang P (2017) Optimizing Design of Two-dimensional Forging Preform by Bi-directional Evolutionary Structural Optimization Method. Procedia Engineering 207:520–525. ISSN 1877-7058. https://doi.org/10.1016/j.proeng.2017.10.815
15. Fourment L, Balan T, Chenot JL (1995) Shape optimal design in forging. NUMIFORM'95 557–562
16. Zhao G, Wang G, Grandhi RV (2002) Die cavity design of near flashless forging process using FEM-based backward simulation. J Mater Process Technol 121(2–3):173–181. ISSN 0924-0136. https://doi.org/10.1016/S0924-0136(01)00998-0
17. Hawryluk M, Jakubik J (2016) Analysis of forging defects for selected industrial die forging processes. Eng Fail Anal 59:396–409. ISSN 1350-6307.https://doi.org/10.1016/j.engfailanal.2015.11.008
18. Di Lorenzo R, Micari F (1998) An Inverse Approach for the Design of the Optimal Preform Shape in Cold Forging. CIRP Annals 47(1):189–192. ISSN 0007-8506. https://doi.org/10.1016/S0007-8506(07)62815-7
19. Vazquez V, Altan T (2000) Die design for flashless forging of complex parts. J Mater Process Technol 98(1):81–89. ISSN 0924-0136. https://doi.org/10.1016/S0924-0136(99)00308-8
20. Park J, Hwang H (2007) Preform design for precision forging of an asymmetric rib-web type component. J Mater Process Technol 187–188:595–599. ISSN 0924-0136. https://doi.org/10.1016/j.jmatprotec.2006.11.034
21. Sedighi M, Tokmechi S (2008) A new approach to preform design in forging process of complex parts. J Mater Process Technol 197(1–3):314–324. ISSN 0924-0136. https://doi.org/10.1016/j.jmatprotec.2007.06.043
22. Fuertes J, Luis C, Luri R, Salcedo D, León J, Puertas I (2016) Design, simulation and manufacturing of a connecting rod from ultra-fine grained material and isothermal forging. J Manuf Process 21:56–68. https://doi.org/10.1016/j.jmapro.2015.11.005
23. Kim H, Kim D (1994) Computer-aided preform design in the closed-die forging process. J Mater Process Technol 41(1):83–104. ISSN 0924-0136. https://doi.org/10.1016/0924-0136(94)90178-3
24. Takemasu T, Vazquez V, Painter B, Altan T (1996) Investigation of metal flow and preform optimization in flashless forging of a connecting rod. J Mater Process Technol 59(1–2):95–105. ISSN 0924-0136. https://doi.org/10.1016/0924-0136(96)02290-X
25. Vargas M, Ramírez E, Ruiz O, Reyes-Ruiz C, Ortiz A (2022) Analysis of the equivalent plastic displacement influence on chip morphology during the orthogonal cutting process using CEL modeling. International Journal of Advanced Manufacturing Technology, Springer. https://doi.org/10.1007/s00170-022-09911-9
26. Messner C, Grass H, Werner E (2002) Reibung und Warmeubergang beim Schmieden 2 (604), VDI Fortschritt-Berichte, VDIVerlag Dusseldorf, ISBN: 3-18-360402-7
27. Grass H, Krempaszky C, Werner E (2006) 3-D FEM-simulation of hot forming processes for the production of a connecting rod. Comput Mater Sci 36(4):480–489. ISSN 0927-0256. https://doi.org/10.1016/j.commatsci.2005.06.003
28. Dieter G (1988) Mechanical metallurgy. McGraw-Hill, UK