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Closed Die Forging Preform Shape Design Using Isothermal Surfaces Method

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Abstract

Preform design is a key step in the development of hot forging processes. Optimal preform shape must ensure complete die fill with minimal flash and reduced forming load while avoiding flow defects like laps. Despite numerous works in this field, preform design is still often based on the trial-and-error method. There is an approach to preform design based on equipotential or isothermal surfaces obtained from a Laplace equation in the domain between two shapes representing the workpiece and the final forging. This method has not been widely applied to practical implementation. It requires proper, but not obvious, selection of the most suitable equipotential surface to be converted to a CAD model to create a preform shape and then creating a die block design based on this shape to perform further optimisation of the technological process by means of simulation. This routine requires several geometrical transformations between simulation and design programs that can be difficult to accomplish using general-purpose CAD programs. In the presented work the authors have integrated QForm metal forming simulation software with a specially developed variant of a CAD system to automate the data transition from finding of the isothermal surfaces used as prototypes of the preform shape with subsequent die blocks creation and further verification of the technology by simulation. The method is illustrated by industrial cases.

Keywords: hot forging; preform design; isothermal surfaces; FEM; QForm

1. Introduction

Quite often hot forging requires several impressions and the most effective design of the series of impressions is a critical issue. The optimal preform shape should provide complete filling of the finish die impression with the minimum material loss to flash, lower forging load, minimised die wear and no flow defects like laps or flow-through defects. There are many works published on this subject so here we mention only some of them to represent different methods.

The technique based on the cross-sections curve method developed by Bryukhanov and Rebelskiy [1] is generally implemented when forging elongated parts placed horizontally. However, this technique cannot be used for forgings with vertically placed workpiece axis. Yu and Dean [2] reviews existing guidelines for the design of die impressions, suggested two new rules and implemented them in a computer program. Park and Kim [3] developed an expert system to automate the process design of axisymmetric hot steel forging. It is a rule-based system written in Fortran and AutoLISP and operates in the AutoCAD environment. To compensate for the insufficiency of blocker design rules, the concept of shape and volume factors was introduced.

Volodin [4] has proposed a system of rules for hot closed forging design that provides a reduction of forging force and saving of material and illustrated its implementation with many industrial cases. Chang and Bramley [5] proposed the inverse simulation approach based on the upper bound method with the finite element procedure used for finding the minimum energy

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required for plastic deformation. In the modified UBET (Upper Bound Element Technique) [6], the velocity fields are derived using a volume mapping approach and evaluated by minimizing the total energy. Lapovok and Thomson [7] presented an approach to optimising the design of preforms for forging an H-section. The principal parameters of the shape are optimised by backward/forward computation according to some preselected criterion such as minimum forging force. Behrens at al [8] developed a method based on FEM simulation. Their algorithm integrates the computer-aided identification of internal folds. For a given process and tool geometry, the area with internal folds is adjusted, until the simulation shows no fold formation. Using the bidirectional evolutionary structural optimization strategy, Shao et al. [9] proposed a new strain-based element addition and removal criterion for the evaluation and optimization of the material flow in the forging process and developed a topological optimization approach to design the preform shape. Park et al. [10] proposed the backward tracing method for tracing the loading path of a forming operation backward from the desired final configuration to the initial form. Biglary et al. [11] present a blocker die design using the backward deformation method. This method employs the FEM analysis during each inverse deformation step. It involves an alternative boundary node release criterion in the simulation of backward tracing of forging processes to reduce the die wear in the finishing operation. Vovchenko [12] used an inverse dynamic programming algorithm and Boundary Element Method (BEM) for the design of preforming dies to optimise forging force and strain distribution inside the forged part

Volodin [13] has developed the software for inverse modelling of axisymmetric parts forging. Recently, Oh and Yun [14] proposed a geometrical method for preform design using the lowpass filter. They separated the frequencies of final shape of the workpiece in the forging process and obtained the smooth shape by adopting the low frequencies in the frequency domain. Then the smooth shape is used for the preform shape.

Lee et al. [15] proposed a method of using equipotential lines and designed the right geometry of preform for symmetric discs. The initial shape (billet) was enlarged sufficiently and the final shape (forging) was located inside the billet shape. Then the voltages of 0 and 1 were applied to the final shape and the initial shape, respectively. In addition, the prefom shape was regarded as that of equipotential lines obtained between the initial and the final shape. Another approach when the initial shape was placed inside of the finish forged part shape was presented by Cai et. al. [16]. In this case, the die was opened along the parting line and the workpiece was placed inside the die impression cavity. Different potentials were applied to the inner and outer cavities and equipotential surfaces were obtained to be used for the die design. Another approach to optimize 3D preform shape in multi-step die forging employed by Guan et. al. [17] was based on quasi-equipotential field method and response surface method. Firstly, the optimum preforming shape was determined by means of quasi-equipotential field method and response surface optimization. Secondly, longitudinal and cross-section curve methods were introduced to design advisable blocking blank based on the optimized preforming shape.

Either approach based on equipotential surfaces requires finding them by means of FEM simulation, selection of a proper surface to create a preform shape and dies, and then providing verification analysis of the material flow by means of simulation. To accomplish such work it is necessary to transform complex geometric objects from FE software to CAD and back to the FE program that makes it difficult to implement this method practically because of the time-consuming manual work when using general-purpose CAD systems.

The presented paper is the further development of the methods published in works [15-17] while probably the earliest works based on electrostatic analogy and potential flow as a first approximation for modeling of material flow in metal forming processes have been done by G.Y. Gun and are summarized in his monography [18]. The main goal of presented development was to make the method of the equipotential surfaces more practically applicable. For this purpose, special software development has been done within QForm metal forming simulation software as well as writing a special add-in QFormDirect to SpaceClaim™ CAD program. The equipotential surfaces were obtained from steady-state temperature field that is a full analogue of the electrostatic field [19] and the software allows simulation of both static thermal task and verification of the deformation process.

2. Theory and software realisation of the method

According to the Helmholtz theorem, any vector field can be represented as a sum of a potential vector field and curl vector field. In the case of a potential velocity field, the velocity vector $\vec{v}$ is a gradient of some potential function φ and can be represented as follows:

$$v_x = \frac{\partial \varphi}{\partial x}, v_y = \frac{\partial \varphi}{\partial y}, v_z = \frac{\partial \varphi}{\partial z} \tag{1}$$

The volume constancy applied to the velocity field $\vec{v}$ in case of an incompressible media can be written as follows:

$$\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy} + \dot{\varepsilon}_{zz} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \tag{2}$$

Substituting (1) into the incompressibility condition (2) we can see that the potential flow function φ obeys the same Laplace equations as an electrostatic field and steady-state temperature field [19]:

$$\nabla^2 \varphi = \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0 \tag{3}$$

This is a so-called electrohydrodynamic analogy between the distribution of the electric potential, the steady-state distribution of temperature and the potential function φ of ideal incompressible fluid flow [18]. Real material flow is not a potential one, and there is a substantial curl vector component in it. Meanwhile, it can be expected that a smaller curl component of the velocity field corresponds to more uniform deformation and less likely formation of laps and flow-through defects. In the presented work we numerically solve the Laplace equation to build isothermal surfaces but it is clear that they coincide with respective equipotential surfaces.

The proposed design methodology uses two software packages. The first one is QForm implemented for simulation of a steady-state thermal field, finding isothermal surfaces and passing them to die design stage. This program keeps the volume constancy in simulation with high accuracy that is very important for a multi-stage forging process development. After the die geometry is completed this program is used for its verification through finite element modelling of the material flow. The second program is QFormDirect, that provides necessary geometric transformations and creation of a die cavity geometry based on isothermal surfaces.

The preform shape and dies are designed using the following routine. Firstly, the forged part geometry is to be added to the system. It can be created in QFormDirect (Fig. 1) starting from a finish machined part geometry. Alternatively, the forged part shape can be imported from any third-party CAD program.

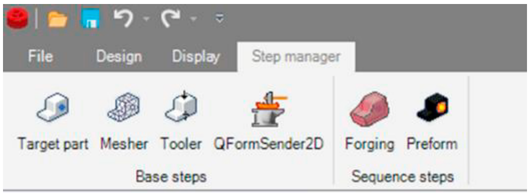

Fig. 1. The toolbar operations in QFormDirect with the buttons to perform the sequence of to create a preform design.

The second stage is the creation of the so-called “thermal assembly” consisting of initial billet shape and finish forged part shape that restricts the domain between them where a steady-state temperature field is to be solved. The obtained isothermal surfaces are to be imported back into QForm-Direct using a special csv3d geometry format that contains a surface as a three-dimensional FE mesh. Then this mesh is to be smoothed and converted into a CAD model. In the current version, such smoothing of 3D FE models is performed in semi-automatic mode while for 2D geometry of axisymmetric parts a special automated design tool has been already developed. In the latter case, this tool provides conversion of a three-dimensional mesh into a plane cross-section to obtain smooth curves of the preform die contours. It is also necessary to specify the zones on the outer surfaces of the preform that will remain free in the finish position of the dies (Fig. 2). Then these curves are to be used to construct the whole contour of the dies and then sent to QForm for the material flow verification simulation.

The convenience of this approach is based on the fact that the dedicated QFormDirect geometry modelling system works in conjunction with the finite element simulation software using specialised geometry import and export tools. To create a preform shape it is only necessary to select a proper intermediate isothermal surface to be used as a part of preform die cavity design and to determine which part of the preform shape surface will remain free at the finish position of the dies. Moreover, by means of using different isothermal surfaces, it is possible to carry out semi-automatic optimisation of the preform shape.

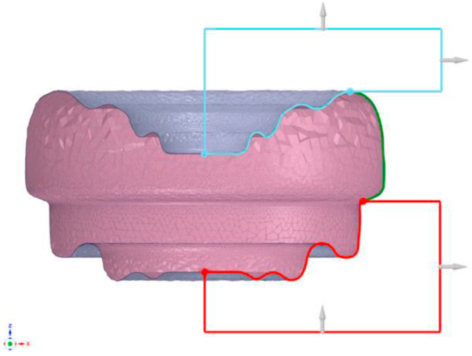

Fig. 2. Smoothed contours of the dies created in QFormDirect using a 3D FE isothermal surface as the preform shape for an axisymmetric part.

3. Design of forging impressions for an axisymmetric part

We considered a sequence of blows when forging a gear blank made of 35XM (GOST) (1.7220 DIN, AISI 4135) steel with overall dimensions of ∅162 × 52 mm. The flash thickness was 2 mm. Two variants of forging technology have been compared: the first variant (two stages) having one preforming operation before finish forging, and the second variant (three stages) with upsetting, preforming and finish forging.

The simulation of the preforming operation in two stages variant has shown a lap formation in the dies (Fig. 3). In this paper a special “Gartfield” indicator (ratio) for predicting surface defects was used [20].

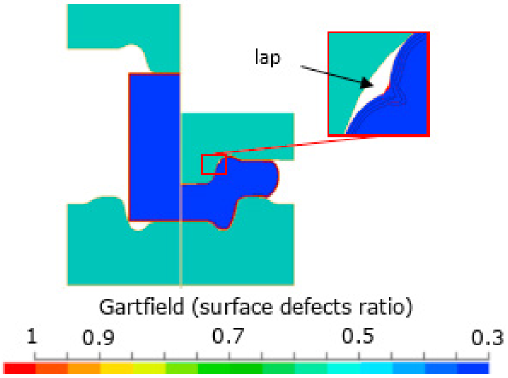

Fig. 3. Lap formation in preforming dies: Initial (left) and final (right) position of the upper die.

Fig. 4 shows the trajectories of some material particles initially located on the upper surface of the workpiece during preforming operation. As we can see they have evident irregularities and intersect the final contour not perpendicularly as it should be in case of potential flow but at certain acute angles. Thus, we can conclude that the metal flow in this case is far from the potential flow.

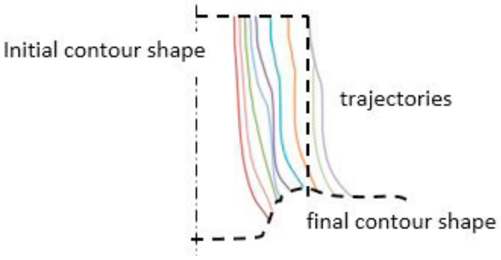

Fig. 4. Trajectories of some material particles initially located on the top surface of the cylindrical billet and following to their final positions during deformation in preforming operation.

Another method to estimate the regularity of the material flow is to compare the maximum strain accumulated during a forming operation with its overall average value in the forged part. According to the simulation results in the first variant, the maximum plastic strain in the first operation was 3.56 while the average strain was 1.13 giving their ratio as 3.15. Such a big ratio indicates a significant non-uniformity of plastic deformation over the workpiece volume.

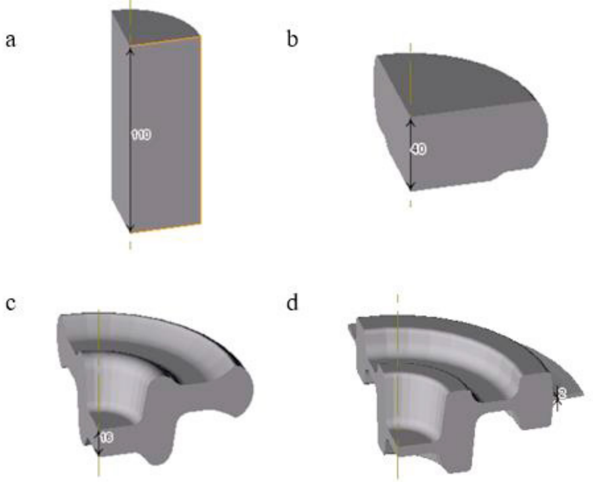

Fig. 5. Three stage process of flange disk forging: the billet (a), upsetting (b), preforming (c) and finish blow (d).

The non-uniformity of deformation can be reduced by the introduction of an intermediate forming operation. Using an upsetting operation before preforming impression (Fig. 5b) reduces maximum strain to average strain ratio below 2.0. Specifically, in the upsetting operation it is 1.97, in the preforming blow it is 1.96 and in the finish forging it is 1.93. In this three stages case, the simulation has shown no material flow defects and the dies have been completely filled at 0.72 mm before the lowest position of the ram. It means that the technological process is stable for a certain variation of the volume of the billet that may happen within admissible tolerances of the manufacturing process.

4. Preform shape design for complex shape parts

The developed technique and software have been implemented for the improvement of forging technology for a gear sector. The workpiece material is a square billet made of steel 55NiCrMoV2 (1.2714 DIN, AISI L6).

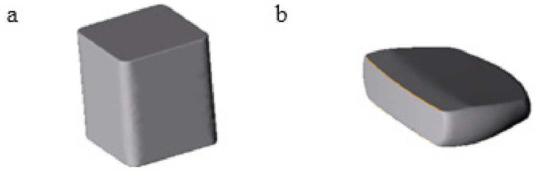

Fig. 6. The upsetting simulation results: the initial billet (a) and the billet shape after upsetting by the dies with inclined surfaces (b).

The initial technology consisted of three operations including upsetting (Fig. 6), preliminary (Fig. 7a) and final forging blows. The teeth shape that was formed in the preliminary impression is close to the finish forged shape. Meanwhile, during the preform step, the part has got laps that are clearly visible in the simulation as clouds of red dots (Fig. 7). Thus, it was decided to implement the developed methodology to modify the preform shape keeping the first operation (upsetting) without changes.

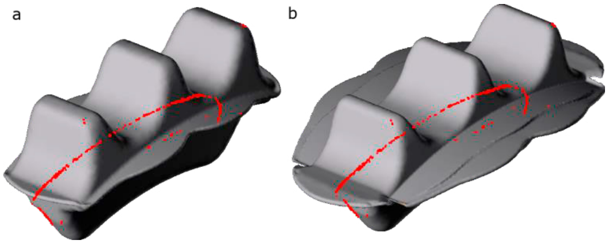

Fig. 7. The initial technology simulation results: the preform (a) and the finish forged part with laps (b).

The deformed shape of the workpiece obtained in simulation was imported to QFormDirect and placed between the finish upper and lower dies to create so-called "thermal assembly", i.e. a domain that includes the space between the billet and dies surfaces and is limited by the vertical surface along the flash land of the dies (Fig. 8).

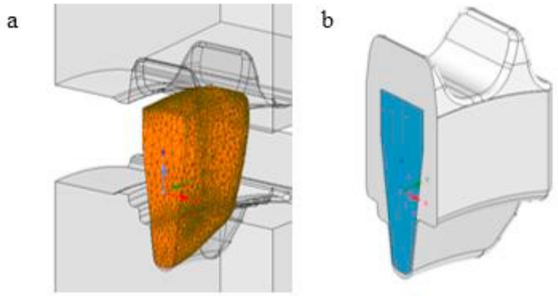

Fig. 8. Making a "thermal assembly": the upset workpiece is placed between the dies (a), the domain ready for simulation of the Laplace equation shown by grey color (b).

The QFormDirect program allows exporting the "thermal assembly" geometry directly to the simulation software. Two different values of the temperature (i.e. 0 and 1) were applied as the boundary conditions to the inner and outer surfaces of the domain (Fig. 9a). In case of two preforming operations the temperature values for selecting isothermal surfaces usually vary from 0.3-0.4 for the first operation to 0.05-0.1 for the second one. The finite element simulation provides the temperature values in nodes within the domain that were used to build an approximation of isothermal surfaces as a set of linear triangular surface finite elements. Then these surfaces were saved in the stl-format (Fig. 9b).

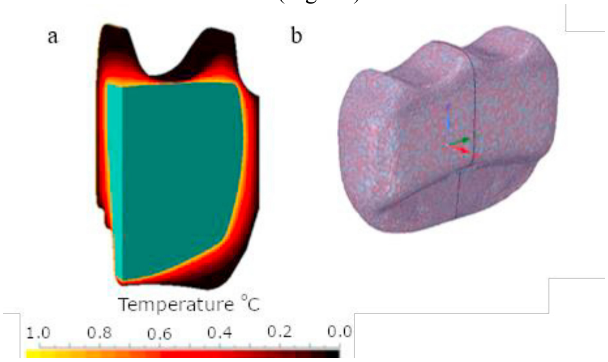

Fig. 9. The steady-state temperature field distribution in a quarter of the domain (a) and one of the isothermal surfaces approximated by finite elements (b).

Then the geometrical models of the upper and lower dies were constructed by Boolean subtracting of the approximation isothermal surface from solid die blocks (Fig. 10a) in QFormDirect program. After completing the design, the newly created dies are ready for verification by means of simulation (Fig. 10b).

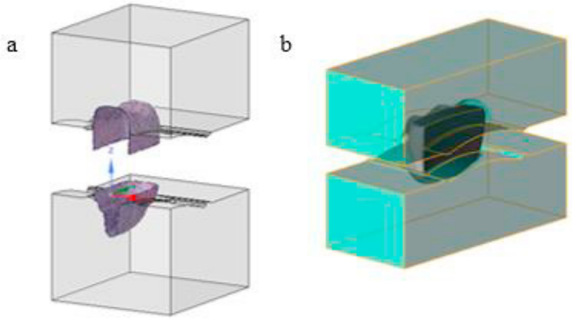

Fig.10. The preform dies design: subtracting of the preform shape from the die blocks (a), the dies and billet before the verification simulation (b).

The results of this verification simulation have demonstrated that there are no laps in the finish impression except some small ones in the flash area that will be trimmed out from the part (Fig. 11).

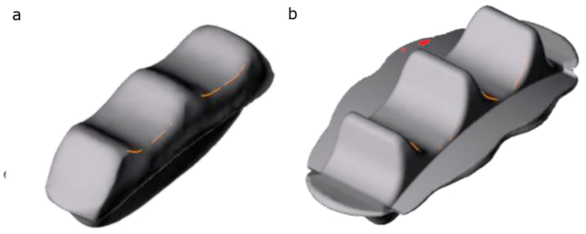

Fig.11. The verification simulation results: the billet after preforming impression (a), the finished forged part with flash (b).

The finish die cavity has been completely filled at 1.5 mm before the lowest ram position that provides a good background for reduction of the billet size and material saving.

Another example of the presented methodology implementation was a preform shape development for a flange forging that has two planes of symmetry. The billet was made of steel 28Cr4 (1.7030 DIN, AISI 5130) having a diameter 100 mm and length 235 mm. Using the described design routine, the shape of the preform has been significantly changed as seen when comparing the pictures in Fig. 12a and Fig 12c.

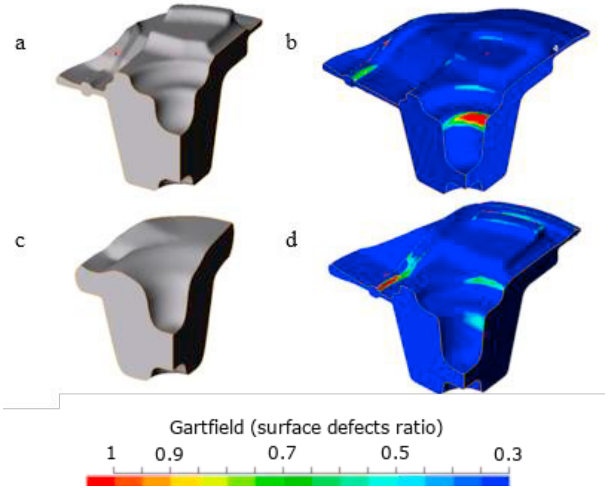

Fig. 12. Flange forging technology improvement: Initial shape of the preform (a) and the respective finish forging (b). Modified preform shape (c) and the finish forging (d). Flow-through defect indicator field is shown in (b) and (d).

As a result of this preform modification, the flow-through defect on the inner surface of the flange has been eliminated. As we can see there are no red zones in the cavity in Fig. 12d comparing to Fig. 12b. The billet length was reduced by 10 mm that saved 4% of the material. The load in preforming impression has been reduced from 20 MN to 8 MN as well as the load in finish blow.

Summary

1. The paper presented further development and practical implementation of the method of isothermal surfaces for forging preform design.
2. Special software development has been accomplished to provide automated bi-directional geometry data transfer

between FEM simulation software and CAD modelling program.

3. Using several practical forging cases, it was shown that implementation of this method ensures avoiding surface defects and reduces material waste.
4. The developed technology is to be implemented in production in the nearest future.
5. Further development of this method will include more automation in 3D die geometry design and its optimisation.

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