AUTOMATED PROCESS DESIGN INTEGRATED WITH NUMERICAL SIMULATION FOR ROLLING, FORGING AND EXTRUSION TECHNOLOGIES.

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ABSTRACT: The paper presents the experience of developing and implementing an integrated approach to metal forming processes design based on simulation implementation. As a simulation tool, we use the versatile QForm UK software incorporated into specially developed CAD software products powered by SpaceClaim ANSYS ®. Three examples of such developments are presented and illustrated by practical case studies, i.e. optimal preform design for hot closed die forging, extrusion dies design and optimisation by automated variation bearing and prechamber shapes and longitudinal rolling pass design. The industrial implementation of such simulation-driven design has proved its high efficiency in significantly reducing the process development time and boosting production performance.

KEYWORDS: simulation, tools, dies, rolls, design, extrusion, forging, rolling

1 INTRODUCTION

Metal forming simulation has become an essential tool for analysing and improving metal forming technological processes. When the simulation is appropriately implemented, it provides an accurate prediction of actual product shape, possible technological defects, strain and temperature distributions and other characteristics which determine the product quality. Nonetheless, the technological parameters of a process are to be specified by the engineer prior to the simulation start. Thus, the search for the best technology still relies on the skills and experience of an engineer even though now he can test different variants of technology using simulation. This provides significant advantages over the "in-metal" trial and error method but may require many iterations to reach good results.

Automated optimisation of the technological parameters can be implemented to speed up the development. It can be done more straightforwardly when it is necessary to find the best value of a particular isolated technological parameter like the billet temperature, tool speed or the upsetting billet height. Meanwhile, in many cases, the real unknown is the best shape of forging, extrusion die, or a rolling groove. In this case, we face the problem of geometry alteration that can be complex and cannot be reduced to finding the best value of some fillet radius or a boss height. Consequently, we have to consider the die shape as an integrity of interconnected geometrical entities and alter them as a whole to achieve the best performance of a forming tool. Thus, this shape alteration must be done using CAD modelling software that, in turn, has to be controlled by parameters that depend on the output of technological process simulation. The goal function can be any reasonable characteristics of the process like the die fill, absence of material flow defects, admissible load, minimum material loss, guaranteed material workout etc. By developing this approach, we are gradually coming to the next level of simulation implementation, which can be called the simulation-driven design of the processes. This paper illustrates it by its application to hot closed-die forging, extrusion and rolling.

2 CLOSE DIE FORGING APPLICATION

2.1 THE USE OF EQUI-POTENTIAL SURFACES

In practice, very few forgings are produced in a single impression. An attempt to achieve complete die filling in one stroke can result in an excessive flash, forging defects, and unacceptable forging load. Usually, one or two preforming operations are necessary to transform the billet material into a shape closer to the finishing die cavity. The number of preforming operations depends on the difference between the beginning billet shape and the finished forging shape and its complexity. The optimal preform shape must ensure complete die fill with minimal flash and reduced forming load while avoiding the flow defects like laps and flow-through.

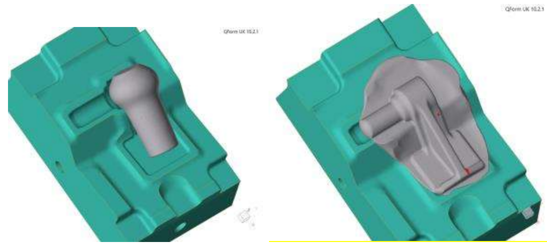
There is a method to develop the preform shape based on potential flow approximation. An explanation of the method, its history and its literature overview can be found in [1]. The potential flow is a hypothetic idealised motion of incompressible fluid with no curl (rotational) velocity vector component and, by these means, makes the formation of any laps or folds impossible. The potential flow velocity vectors are always perpendicular to equipotential surfaces obtained as a solution of the Laplace equation obtained in the flow domain. In the case of a closed die forging process, the domain for the Laplace equation can be created between two appropriately scaled surfaces representing the workpiece and the finish forging, respectively. Of course, the actual material flow in forging is not a potential one and has a curl velocity vector component. Meanwhile, it was practically found that the use of equipotential surfaces as a guess for a preform makes the formation of flow defects less likely and provides the complete fill of a finish die much easier.

2.2 FORGING CASE STUDY. INITIAL ATTEMPT

The software QForm Direct, based on this method, has been implemented in several hot forging jobs, and all of them have proved the efficiency of the developed preform shapes. Below is presented one of such cases where we developed the preform for the hot forged arm shown in Figure 1. The initially proposed technology used a round bar billet with a diameter of 48 mm and height of 190 mm made of steel C35 (1-05017 DIN) heated to 1100^{0}C that was upset to 130 mm to form a "bulb" that was expected to fill the finish die cavity in its most massive zone of the forging. The equipment was a 16 MN mechanical press.

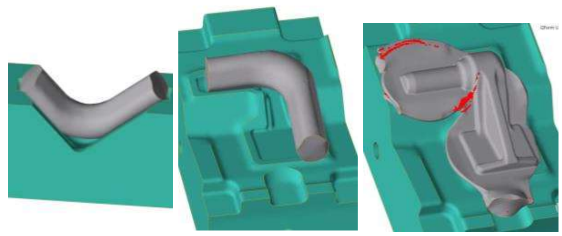
Figure 1: The arm: the model of the finished forged part.

The simulation has shown that such a "bulb" preform does not provide proper material flow to fill the die in the shaft zone (Figure 2b). The next attempt was to bend this billet and place it in finish dies (Figure 3). In this case, the shaft area was completely filled while the massive lap appeared in the shaft-to-arm transition zone (red mark in Figure 3c).



a. b.

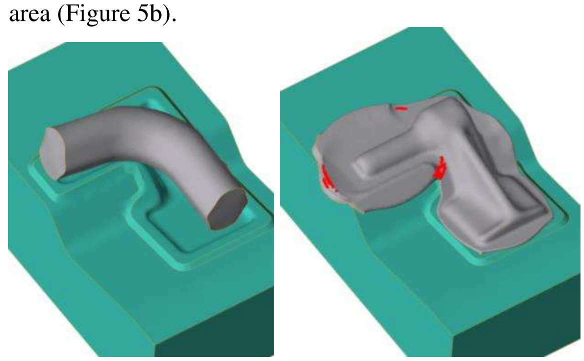
Figure 2: The "bulb "preform in the finish dies.



a. b. c.

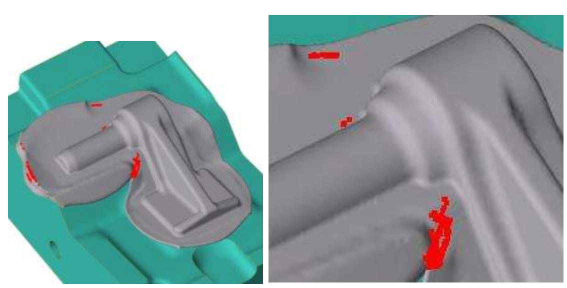
Figure 3: The bent preform billet placed in the finish dies.

Then using QForm Direct, a special preform and preformig dies have been developed (Figure 4). The simulation has shown no laps in this preform. Then it was placed in the finish impression where the material completely filled the die cavity, and no laps were indicated. As we see, the red marks are only in the flash area (Figure 5b).



a. b.

Figure 4: The bent preform forged in developed preform dies.



a. b.

Figure 5: The finish forging using the developed preform: (a) general view, (b) magnified fragment.

The developed preform dies have been manufactured and tested in production (Figure 6). The finished part was carefully inspected, and its quality was perfect (Figure 7).

Figure 6: The finished forged part in a hot state.

a. b.

Figure 7: Comparison of the real finished forged part after cooling and cleaning (a) with simulation (b).

3 AUTOMATED DESIGN AND OPTIMISATION OF EXTRUSION DIES

3.1 BEARING AND PRECHAMBER VARIATION

The geometric design of the die set is crucial for the extrusion process performance and product quality. Three essential elements of the extrusion tooling set significantly impact the profile's exit velocity. Namely, they are ports, prechamber and bearings.

Automated optimisation of ports is a challenging task that is still difficult to formalise, and it is not considered in this paper. On the other hand, bearings length and prechamber configuration can be varied independently of the other die elements, even though their variation has limitations. Generally, bearings should not be too short of ensuring the required tool life or too long when they become ineffective. The prechamber shape variation is limited between the welding chamber contour and the profile contour. However, since it's practically the easiest way to adjust the tool to balance the material flow without significant structural change of the die set, bearings and prechamber variations play an essential role in the tool correction and designing. Consequently, they also may be subject to automated optimisation based on simulation [2].

3.2 CAD-SIMULATION INTEGRATION

The proposed approach to optimisation of the bearing and prechamber schematically is explained in Figure 8. The first step is a preliminary design of the extrusion tooling set, starting from a profile drawing using our purpose-built CAD program QExDD (QForm Extrusion Die Designer). With its help, the user creates a general shape of the toolset, including support components. Special bearing, prechamber, and relief editors automate the most labor-consuming design operations. The program speeds up the work and stores the created shapes in a parametric form that is essential for optimisation. Then the technological process parameters are added (alloy, temperature, extrusion velocity, etc.), and the process is transferred to the simulation program. As soon as the simulation is completed, its results are returned to the design program that uses different optimisation algorithms to vary the geometry of the prechamber and bearings to reduce the velocity non-uniformity until convergence is reached.

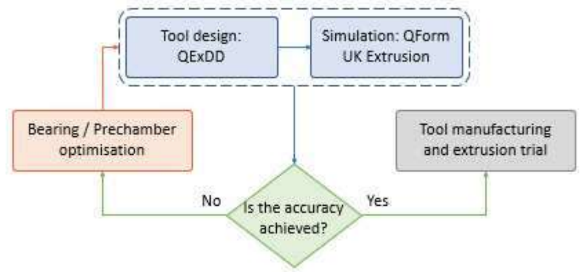


Figure 8: Schematic flow chart of the bearing and prechamber optimisation.

3.3 OPTIMISATION PROCESS

The main goal of bearings and prechamber optimisation is to balance the flow of the profile. Using the finite elements method (FEM) notations means that the absolute velocity value (V_i) in each node (i) has to be as close as possible to the average profile velocity (V_{aver}) that is calculated as follows:

$$V_{aver} = \left(\sum_{i=1}^{n} V_i \right) / n, \tag{1}$$

where n is the total amount of nodes in the profile.

From a mathematical point of view, the optimisation of profile flow can be formulated as a minimisation of the variance (σ_V^2) of velocity distribution in the profile:

$$\sigma_V^2 = \sum_{i=1}^{n} \frac{(V_i - V_{aver})^2}{n-1} \tag{2}$$

Obviously, the variance is equal to zero for an ideally balanced flow.

Three ways of optimisation are available in QExDD: subsequent optimisation, batch optimisation and an approach combining the abovementioned methods. In the case of prechamber optimisation, the variable parameter is the distance between the bearing contour and the prechamber wall. In the case of bearing optimisation, its length varies along the bearing perimeter.

Subsequent optimisation. This way of optimisation allows guaranteed step-by-step improvement of the profile flow. In this case, the same correction parameter is used in the optimisation formula for each optimisation iteration until the required convergence is reached. It allows the user subsequently get closer to the desired result by automated modification of the tool geometry.

Batch optimisation. This way of optimisation allows running simulations in parallel with different correction parameters of the optimisation formula. Thus, this method allows getting the most appropriate correction parameter for the design, ensuring the minimum velocity variance.

Combined approach. This way of optimisation combines the advantages of both previously described types. Firstly, batch optimisation is used to find an optimised value of the correction parameter, and then this parameter is used for subsequent optimisation.

3.4 PRECHAMBER OPTIMISATION

This is the case of a prechamber optimisation where its contour was varied along the profile perimeter while the bearing had a constant 4 mm length. Figure 9 shows the initial prechamber design based on constant offset (brown line) and respective field of the velocity variation across the profile. After four iterations, the prechamber configuration changed to the blue one.

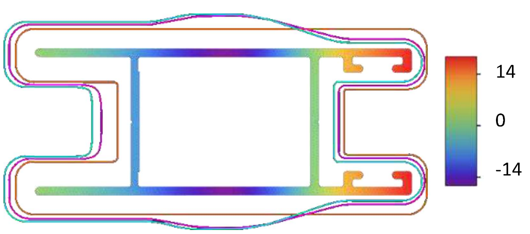


Figure 9. Velocity deviation distribution (%) for the initial prechamber designs (brown contour) and contours of intermediate (magenta) and final (blue) configurations.

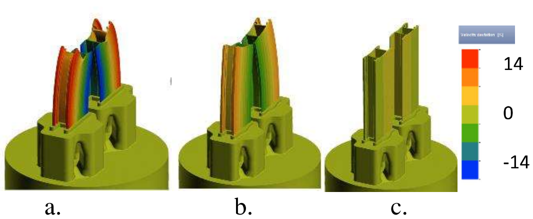


Figure 10. Velocity deviation distribution (%) for different prechamber designs: a – initial, b – intermediate, c – optimised.

The shapes of the extruded profiles for different variants of the prechamber configuration are shown in Figure 10. As we see with an optimised prechamber, the profile is straight while its velocity variation is nearly zero.

4 ROLL PASS DESIGN AND SIMULATION

4.1 ROLLING SIMULATION

Over 90% of all materials that are subject to deformation are rolled. Rolling provides billets for other forming processes like forging but also produces finish products such as beams, rails and other shape profiles for construction, machine-building and railroads. The shaped rolled products are made in many passes, which gradually change the cross-sectional shape of the ingot to the finish profile configuration. Some profiles as rails have very tight tolerances that are difficult to achieve without costly trials in the mill. The numerical simulation helps analyse the material flow within each rolling stand, including the spread and filling of grooves, predicts the load and torque in every stand and shows how rolling stands interact with each other in a continuous rolling mill. The rolls can be driven by motors or be idle, getting rotation from the product as in universal stands (Figure 11). To speed up the simulation of the rolling process using FEM, a special module has been developed in the QForm UK program. It implements a dual mesh method for the deformed material, the Euler approach for the rolls, special technique for treating contact conditions between rolls and metal. More detailed information on the specifics of the rolling simulation and its experimental verification can be found in [3].

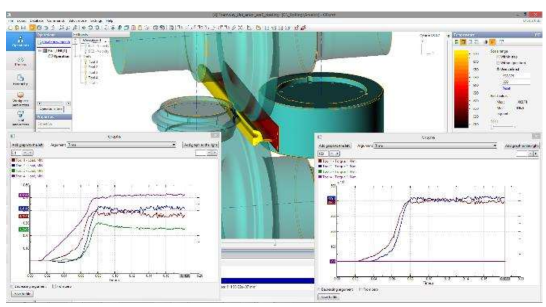


Figure 11. General view of QForm UK rolling module when simulating rail rolling in a universal stand with shown load and torque graphs of driven and idle rolls.

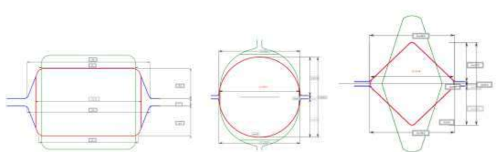
4.2 ROLL PASS DESIGN

Meanwhile, the success of the rolling technology development largely relies on the quality of roll pass design, a sophisticated skill requiring many years of experience. There are numerous published and internal companies' guides on designing roll passes for different types of mills. Such empiric guides acceptably work for simple profiles but usually cause difficulties when developing the pass design for complex shapes like beams, rails etc. To speed up and automate roll pass design, a special CAD program QForm "Kaliber", has been developed. It integrates both pass design and FEM simulation of rolling, including groove shape creation, technical documentation preparation, and source data generation for simulation. This program provides:

- Storing the technical specifications of rolling mills for roll pass design and simulation
- Creation of an inventory of existing rolls
- Design of roll groove shapes, estimation of the temperature, speed parameters of a rolling process, rolling loads and torques
- Analysis of rolling processes taking into account the limitations imposed by the mill specifications
- Visualisation of roll passes by placing the product cross-sections before and after the roll for estimation of bite conditions and deformation in different parts of the rolled profile
- Keeping archives of groove shapes regarding variation versions
- Creation of essential technological documentation: drawings of grooves and rolls, set-up diagrams, rolling schemes
- Automated preparation of source data for rolling process simulation in QForm UK
- Presenting the results of simulation over the designed drawing of the grooves for their visual control.

CAD "Kaliber" supports the following types of passes (Figure 12):

- Box pass with various bottom shapes,
- Round/oval and their variations,
- Square/rhombic and their interpretations,
- Closed/open passes for rolling angle, I-beams, T-beam, channels (and shaped blanks),
- Universal passes for rolling all shapes,
- Passes for mine support profile

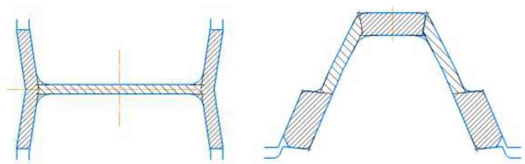


a. b. c.

Figure 12: Some of the standard pass shapes in parametric representation in" Kaliber": (a) box, (b) oval, (c) rhomb.

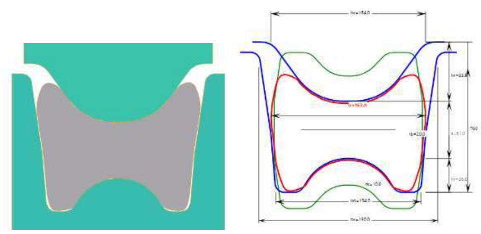
More complex shape sections like I-beam, T-beam, channel, zee beam, and rail are designed using sub-elements division. The deformation in these elements is initially estimated individually and then verified and corrected by simulation (Figure 13).

CAD "Kaliber" also possesses the facility of fast simulation based on the so-called 2.5D approach when the deformation in the longitudinal rolling direction is supposed to be constant. This option is helpful because it immediately shows the deformation of a cross-section, how the metal fills the groove and where it is necessary to alter the grove shape. Then the designed shape of a pass can be verified by full 3D simulation (Figure 14).



a. b.

Figure 13: I-beam (a) and mine support profile shape (b) divided by sub-element for initial stage of design.



a. b.

Figure 14: 2.5D simulation of the crosscut deformation (a) and overlapping of the obtained configuration shown by red with blue contours of grooves (b).

The three previously presented simulation cases integrated with the computer-aided design for forging, extrusion and rolling are based on different principles. Nonetheless, all of them show a synergetic effect for practical benefits. It opens the way to develop technologies that save material, reduce tooling costs and require less time compared to the separate use of simulation and computer-aided design. This approach also opens the way for the implementation of optimisation based on various criteria such as productivity, quality and others. Integration of simulation and process design through the whole production chain is within the concept of Industry 4.0 and has excellent prospects.

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