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Automated Optimum Extrusion Die Design and Profile Quality Control Based on Simulation

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Abstract. The paper presents the experience of development and implementation of an integrated approach of extrusion simulation with the automated design of the dies as a new way to speed up the technology development and its optimisation based on the QForm UK Extrusion simulation program and QForm Extrusion Die Designer (QExDD) design system. Bearing and prechamber optimisation types are considered for the porthole design. Welding quality and possible streaking lines in the profile are analysed for the tool construction with optimised prechamber contour.

Introduction

Rapid electrification of automotive transport has significantly increased demand for high-strength aluminium alloy profiles. Competition among producers demands that the aluminum industry produce extrusions quickly with the highest shape accuracy. Therefore, the rapid development of effective extrusion technology becomes vital which defines the need for a modern approach to process analysis i.e., numerical simulation.

The article discusses the importance of considering various parameters when designing a new die set, apart from just the profile flow. To illustrate this point, the analysis of other parameters relevant to the final product requirements is provided. The most challenging defects resulting from die design are identified as welding quality of longitudinal seams [1], underfilling of the profile [2], and streaking lines [3].

Numerous techniques and approaches exist for extrusion tool design. Noteworthy publications [4]-[5] offer general guidance on tool design, ranging from drawing the hot profile and determining its position on the die to constructing the welding chamber of the tooling set. Additionally, new methods for extrusion tool design have emerged, encompassing various specialized techniques. One such example is presented in work [6], which introduces a novel design quality estimation method. This method utilizes the difference in bearing length within a local coordinate system, as opposed to commonly employed global coordinates.

The applicability of machine learning and artificial intelligence (AI) in porthole die design is explored in the works of authors [7]-[8]. These studies highlight the potential of using AI and machine learning techniques in the context of porthole die design. Furthermore, the design of porthole extrusion dies is extensively covered in the article [9]. The paper focuses on an optimisation process based on a Pareto-based genetic algorithm, aiming to demonstrate an integrated solution that combines a CAD-design system for extrusion dies and finite element method (FEM) simulation with an automated optimisation procedure.

Overall, the article emphasizes the need to consider multiple parameters and introduces various techniques and methodologies for die design, showcasing advancements in the field and the potential of integrating CAD-design systems, FEM simulations, and optimisation procedures.

Initial data for numerical simulation is a 3D model of the tooling set for which all forming surfaces, basic contours, and dimensions have to be as close as possible to the real tool to ensure the practical value of simulation results. A typical extrusion die set consists of a mandrel, die plate, and backer

(Fig. 1). Despite the great variety of the forming surfaces defining different conditions of flow there are three basic elements of the tooling set the modification of which directly affects the exit distribution of velocities in the profile: ports, prechamber, and bearings.

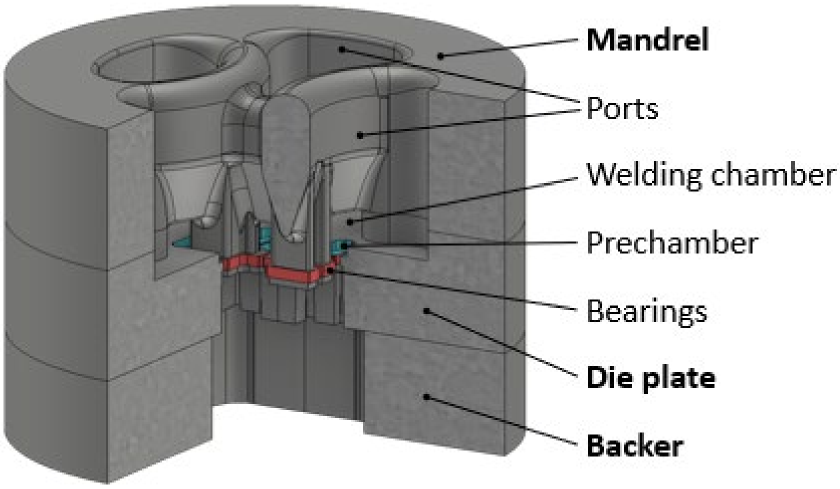

Fig. 1. Simplified representation of porthole die set for aluminium profile extrusion

Automated optimisation of ports is a complicated task that affects not only the flow balance of the profile but other output parameters of the extrusion process and the tool structure itself which defines deflection and tool life respectively. Whereas bearings and prechamber modification don't lead to a significant change in extrusion parameters except for velocity distribtuion, although in some cases may slightly affect charge weld propagation and surface quality of the profile.

Bearings and prechamber have limitations in influencing the profile flow depending on the type of the profile, its thickness, and other geometrical specifics of the process. Thus, in the case of a poorly designed tool, it's impossible to balance the flow by varying bearing heights or prechamber shapes. In general, bearings should not be too short to ensure the required tool life but there is also no sense to make them too long since deformation during the extrusion process leads to inclinations of bearing surfaces since friction is only applied on some effective length with the bearing in excess of this length causing no impact on local velocity of the profile. A similar limitation applies to the prechamber: its contour is limited by the welding chamber contour from one side and by the profile contour from the other side. However, since it's practically the easiest way to adjust the tool and improve the flow without significant structural change, bearings and prechamber play a significant role in the tool correction and designing.

CAD-CAE Combination

The proposed approach to optimal technology design includes several steps (Fig. 2). The first step is a preliminary design of the extrusion tooling set using a profile drawing. Using built-in algorithms and specialised tools, the user creates the general shape of the tool set including support components. At the same time, the most labor-consuming parts of the work are automated by specialised bearing, prechamber, relief and other contour editors. This method significantly speeds up the work and stores the created shapes in the parametric form that is the most important for subsequent optimisation. Then the other process parameters (alloy grade, temperature, extrusion velocity, etc.) are added and the process data are transferred to the simulation. 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 or bearings to reduce the velocity non-uniformity until convergence is reached.

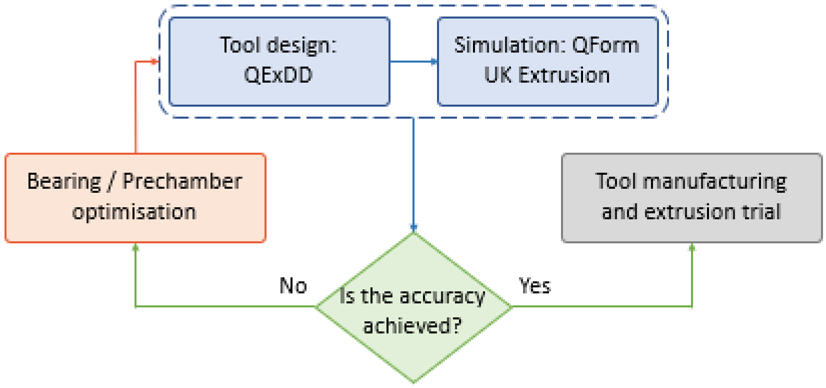

Fig. 2. Graphical representation of the optimisation integration of CAD and CAE

Optimisation Process

Traditionally the design verification iterations were carried out manually, which increased the requirements for the designer's skills: based on the analysis of the simulation results they had to improve the model according to possible correction strategies [10]-[11]. Meanwhile, automated optimisation eliminates routine steps of simulation setup and further geometry re-preparation. Furthermore, optimisation allows the user to skip the correction step since CAD-CAE chain automatically improves the model using optimisation algorithms according to the simulation results.

As it was mentioned before, the optimisation of ports is an extremely challenging task since it affects many aspects of the extrusion process. This is why the main automatization attempts in case of port modifications are focused on the development of the methodology of how to make an initial design of the ports good enough for further bearings/prechamber adjustment in case of unbalanced flow or how to re-design ports based on simulation results [12] but not how to correct them.

The main goal of bearings [13] or prechamber [14] optimisation is to balance the flow of the profile. Using finite elements method (FEM) language it means that absolute velocity value (V_i) in each node (i) has to be as close as possible to 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:

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

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

In QForm UK Extrusion simulation there is another distribution used for quantitative analysis of the flow imbalance – velocity deviation (VD) that is calculated as follows:

$$VD = \frac{V_i - V_{aver}}{V_{aver}} \cdot 100\% \tag{3}$$

The utilization of this distribution enables the assessment of flow imbalance as a percentage of the average profile velocity. A positive sign indicates a higher profile velocity at a specific location compared to the average, while a negative sign signifies the opposite. Hence, the objective is to minimise the deviation in velocity along the entire profile contour, striving for a value as close to zero as achievable. Essentially, this parameter corresponds to the relative velocity (VR) of the profile, employed in QExDD interface, and its calculation can be expressed as follows:

$$VR = \frac{V_i}{V_{aver}} \tag{4}$$

For the VR parameter, values exceeding 1 indicate regions of the profile with velocities higher than the average, while values below 1 indicate the opposite. The optimisation objective in this scenario is to achieve a relative velocity of 1. Consequently, the ultimate goal is to get the VD (velocity deviation) and VR (relative velocity) obtained from the FEM simulation as close as possible to the respective aiming values.

The optimisation scheme depicted in Figure 3, encompasses the definition of initial bearings and prechamber, as well as the addition and removal of tool material in the respective components through the optimisation procedure.

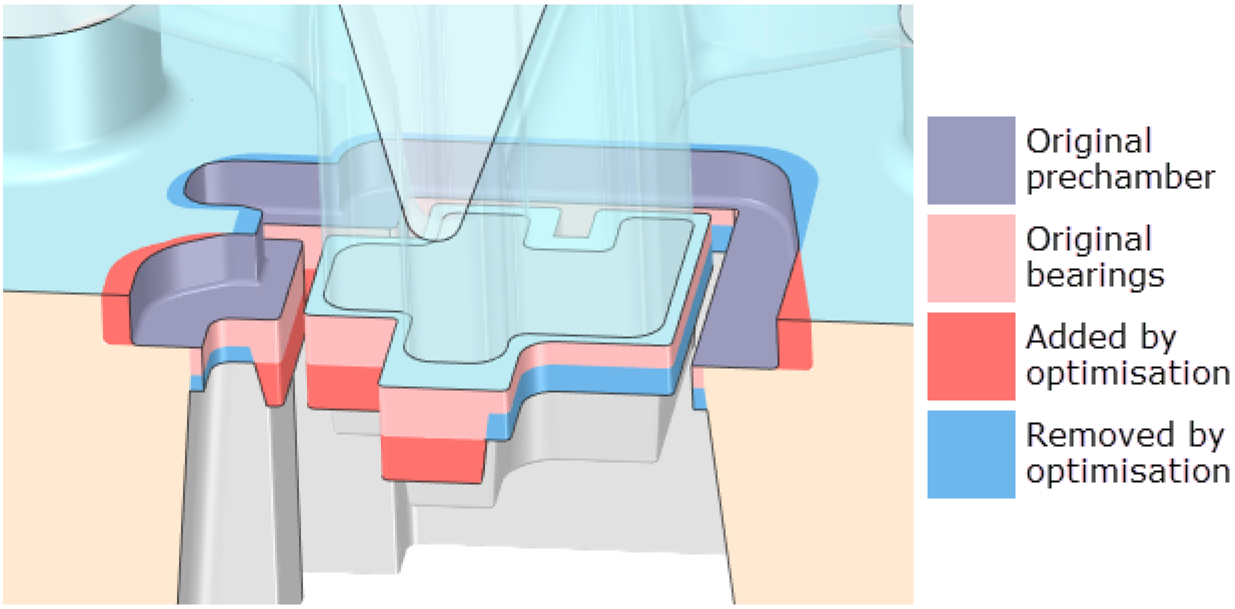

Fig. 3. On the explanation of optimisation procedure

After conducting the simulations, the objective of optimisation is to determine the optimal coefficient (k) that governs the influence of relative velocity (VR) on the modification of prechamber offset or bearing length thereby ensuring a uniform profile flow. This coefficient is incorporated into the correction formula, which controls the adjustment of the prechamber offset (o_i) during prechamber optimisation, or the bearing length (l_i) during bearing optimisation:

$$o_i = f(o_{0i}, k, VR), \tag{5}$$

$$l_i = f(l_{0i}, k, VR), \tag{6}$$

where o_{0i} and l_{0i} – initial values of the prechamber offset and bearing length respectively.

There are three ways of optimisation available in QExDD: subsequent optimisation, batch optimisation and combined approach. In the case of prechamber, the variable parameter is the distance between the bearing contour and prechamber wall, whereas for the bearings it is height.

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 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 optimisation formula. Thus, this method allows getting the most appropriate correction parameter for the design ensuring the minimum of velocity variance.

Combined approach. This way of optimisation combines the advantages of previously described types. Since subsequent optimisation doesn't ensure fast convergence using the default value of the correction parameter but batch optimisation finds the optimal one, then the combination of these two approaches allows faster minimisation of velocity variance. Thus, first of all, batch optimisation is used in order to find an optimised value of the correction parameter, and then this parameter is used for subsequent optimisation.

Application of the Optimisation Methodology

In this work, a porthole die set for the extrusion of a hollow profile with (1.6-2.2) mm thickness was designed in order to investigate the capabilities of the optimisation engine of QExDD based on the simulation results obtained in QForm UK Extrusion.

This work aims to present a case study for industrial tool design. The design of the ports was deemed acceptable and sufficiently accurate, allowing for further flow improvement by adjusting other components. Consequently, optimisation was carried out by automating the variation of bearing length and prechamber offset.

Process parameters and geometrical details of the process are listed in Table 1. For this project, bearings and prechamber optimisations were used separately in order to check the sensitivity of the optimisation process to different optimisation variables and to discuss the limitations of these variables.

Table 1. Technological and geometrical parameters of the project

Parameter	Value
Alloy	AA 6063
Extrusion ratio	74.2
Container temperature [°C]	430
Billet temperature [°C]	480
Tool temperature [°C]	450
Extrusion velocity [mm/s]	5
Billet length [mm]	1000
Billet diameter [mm]	203
Container diameter [mm]	210

Bearing optimisation. The original design of this project contained certain prechamber contour and flat bearings with 4 mm height without transitions. For this design, the simulation showed a significantly unbalanced flow. However, after the first iteration of optimisation process, the simulation showed a much more uniform flow and predicted the ideal flow for the second iteration (Fig. 4).

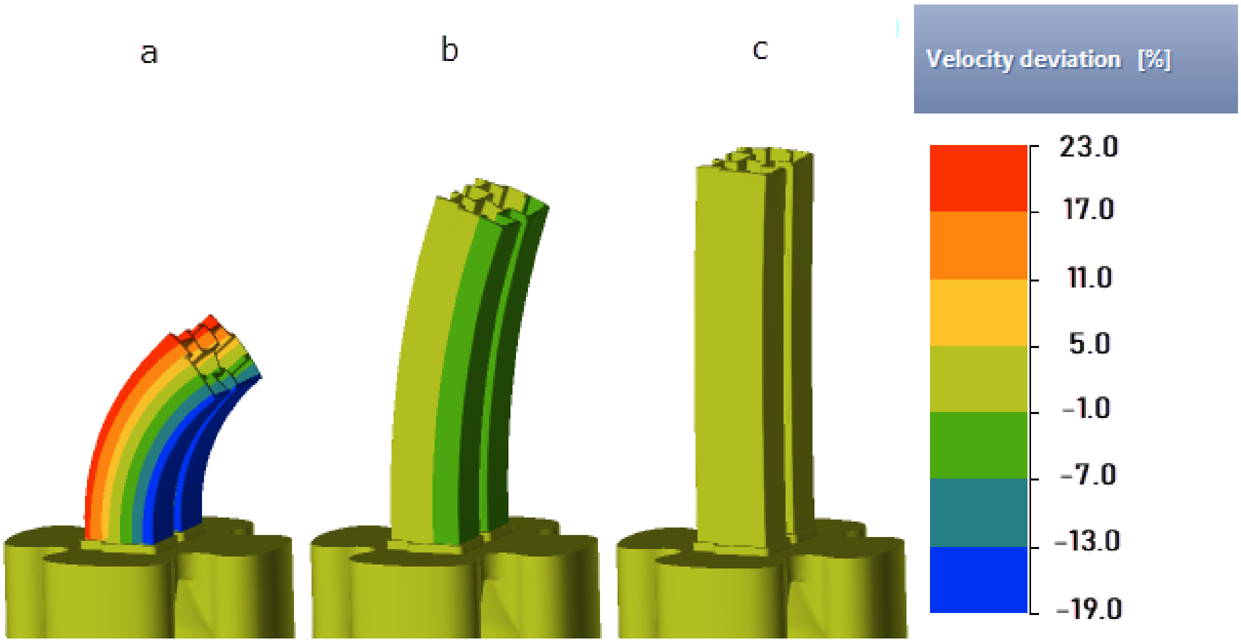

Fig. 4. Velocity deviation (3) distribution for different bearing designs: a – initial, b – intermediate. c – optimised

Bearing maps generated during the optimisation process are presented in Figure 5. As can be seen, the difference in bearing heights for the optimised construction was about 6 mm which is quite a lot for this kind of profile. Additionally, the minimal height of the bearing was set to be equal to 1.3 mm which is in general too short for a profile of a designed thickness. This basically means that the quality of the initial design of the ports isn't sufficient to allow profile flow adjustment by bearings modification alone.

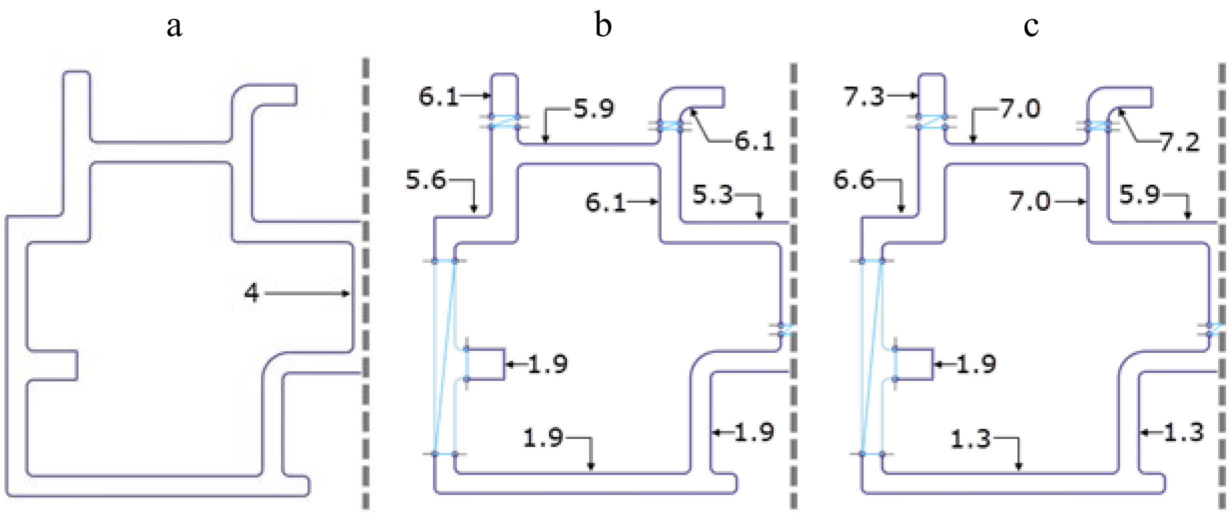

Fig. 5. Bearing maps for different designs: a – initial, b – intermediate, c – optimised

Prechamber optimisation. In this case, the prechamber contour was varied for the design with 4 mm height flat bearings. In a similar way to the bearings optimisation process, the goal of optimisation was achieved for the second iteration (Fig. 6). Unlike the bearings, the variable contour of the prechamber has a geometrical limitation as the profile contour from one side and the welding chamber from another, therefore the algorithm follows these rules by default while optimising.

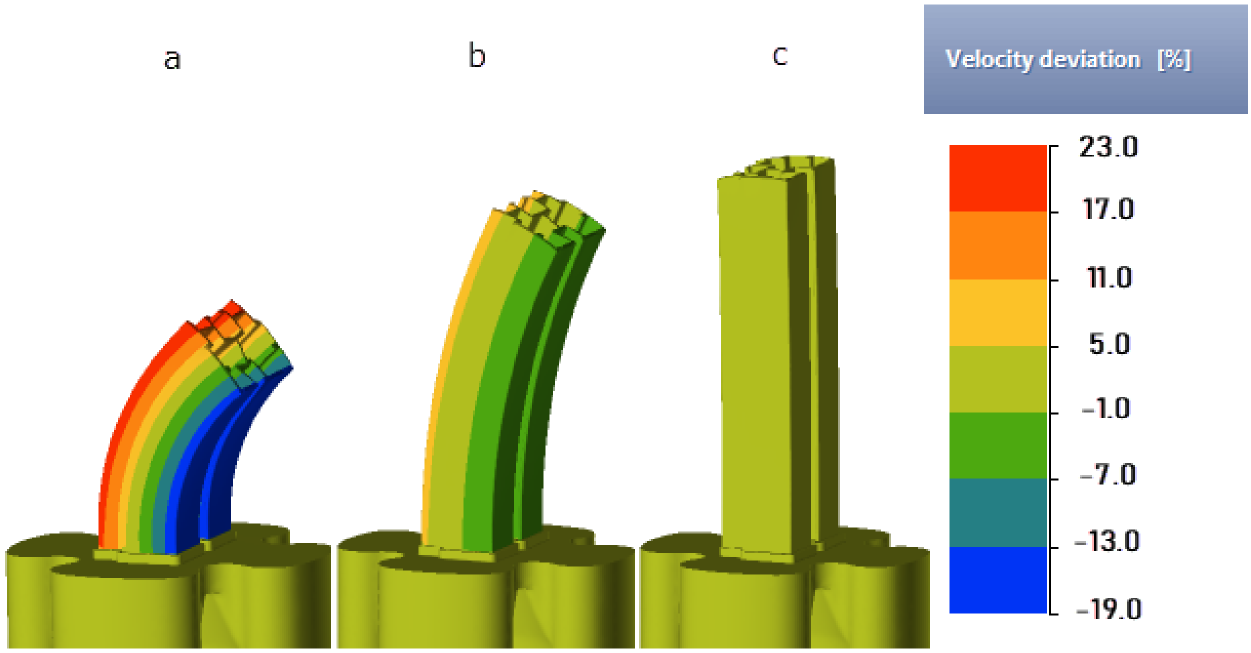

Fig. 6. Velocity deviation (3) distribution for different prechamber designs: a – initial, b – intermediate. c – optimised

Initial and generated contours of prechamber as well as the distribution of relative velocity for the initial design are presented in Figure 7. It's clearly seen that for the places where the profile flowed faster, the prechamber contour got closer to the profile which allowed the reduction of the material stream through the considered place, whereas for the slow parts the contour got wider.

For reference, respective values of velocity variance for different bearing designs and prechamber contours are presented in Table 2.

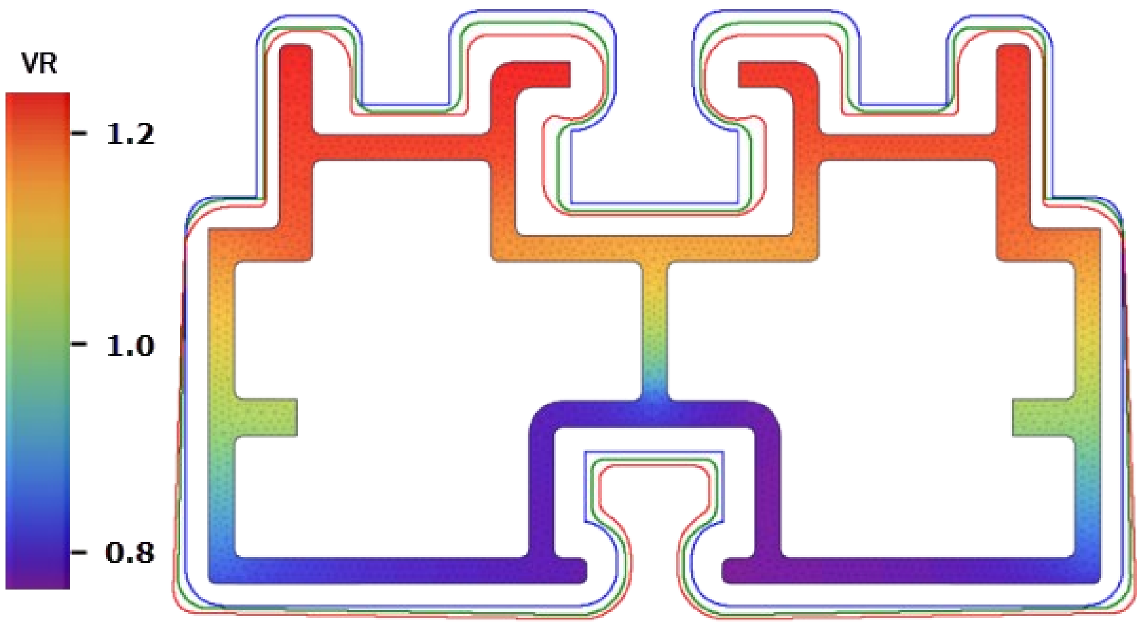

Fig. 7. Distribution of initial relative velocity (4) with prechamber contours: blue – initial, green – intermediate, red – optimised

Essentially, although velocity variance is relatively less for the bearings optimisation, the prechamber optimisation is preferable for this project since it ensures reliable tool design within geometrical limitations common for the extrusion tools.

Profile Quality Control

In general, achieving uniform material flow in profile extrusion doesn't guarantee the complete optimisation of the design. Therefore, it is essential to analyse other parameters such as tool stress, deformation, and profile quality indexes using simulation results. By varying appropriate technological or geometrical parameters, these aspects can be improved [15]. This implies that the optimisation process should consider not only flow as the objective but also factors like tool life, welding quality, charge weld length [16], back-end defects [17]-[18], microstructural defects [19]-[21] and more. Consequently, the optimisation process becomes more time-consuming and complex.

Additionally, the requirements for profiles are directly linked to their practical applications. For automotive profiles, welding quality [22]-[23] is a crucial parameter in quality control, while decorative profiles prioritize the quality of visible parts on the surface of the final product. One well-known defect that significantly affects profile surface quality is streaking, which appears as shaded lines darker or lighter than the core material [24]. Therefore, the absence of streaking lines and high welding quality are vital for ensuring the profile meets high standards, regardless of its intended application.

This means that the optimisation function should offer flexibility to include or exclude specific objectives based on the specific requirements. This conclusion sets the direction for the further development of automated optimisation in the extrusion industry.

Figure 8 presents the results of calculations using QForm UK's built-in streaking lines criterion and welding quality index. It is evident that all streaking lines are either located on the corners or on the inner surfaces of the profile. Moreover, the welding quality index is close to or exceeds 1 for the welding seams, indicating the formation of strong structural bonds between metal streams.

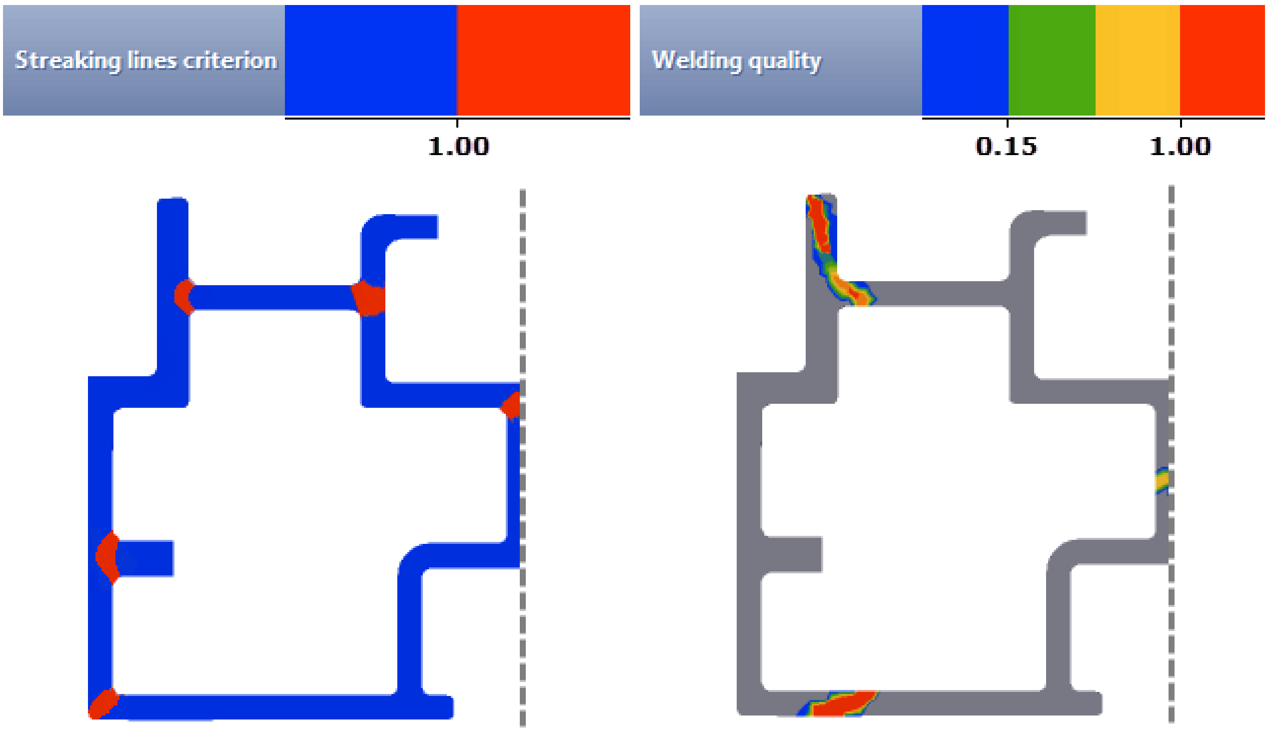

Fig. 8. Streaking lines (left) and welding quality (right) distributions calculated for the omtiimised design

Conclusions

As a summary, the presented work allows to draw the following key conclusions:

- Flow optimiser of QExDD together with simulation in QForm UK Extrusion allows reliable automated bearing and prechamber optimisation

- Both bearings and prechamber have limited possibility to influence the flow. Ports design defines the possibility to improve the flow by bearings adjustment or prechamber modification
- Automated optimisation is possible only when the modification process doesn't negatively affect the structural specifics of the tooling set. Therefore, the optimisation of the prechamber and bearings is practically safe and reasonable
- After the straight and uniform material flow is reached, the other parameters of the profile quality can be analysed using the results of simulation depending on the application of the final product
- The proposed integrated approach has shown its great practical applicability and it follows the general trends of Industry 4.0

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