# Comprehensive analysis of waving defects in aluminium profile extrusion

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**Abstract.** Waving defects in extruded aluminium profiles pose significant challenges to achieving the stringent geometrical tolerances required in industries such as automotive manufacturing. These defects, driven by flow velocity and thermal gradient imbalances, often emerge during later stages of the extrusion process, complicating early detection and mitigation efforts. This study investigates the mechanisms underlying waving defects through comprehensive simulations of industrial and benchmark profiles using QForm UK software. Critical insights into defect formation were achieved by analysing flow velocity and thermal variations across the extrusion process. The results highlight the interplay between feeder plate design, central feeding mechanisms, and billet discard length in influencing velocity deviations and subsequent wave formation. Moreover, the study demonstrates the importance of full-billet simulations in predicting these defects, as simplified approaches often fail to identify critical hidden variables. Practical recommendations are proposed to minimise waving defects and ensure high-quality, defect-free extrusions. These findings offer valuable strategies for advancing extrusion process design and meeting the rigorous demands of modern industries.

## Introduction

The demand for lightweight, geometrically precise components has steadily risen in industries such as automotive manufacturing, where aluminium has become a replacement for traditional materials like steel. Aluminium's versatility and lightweight properties make it an ideal choice for producing complex profiles, particularly through extrusion processes. However, ensuring compliance with the precise geometrical tolerances required by automotive applications presents substantial challenges. Among these, waving defects that have a form of shape variation caused by imbalances in flow velocity during extrusion stand out as a critical issue.

Waving defects can lead to unacceptable deviations in profile geometry, ultimately compromising product quality and functionality. The phenomenon often develops late in the extrusion process, driven by thermal and velocity imbalances that are difficult to predict using standard simulation methods. While traditional approaches consider velocity distribution in steady-state, they frequently overlook transient velocity variations that influence defect formation. To address this gap, advanced simulations are necessary to capture the complex interplay of thermal, mechanical, and geometric factors over the entire extrusion cycle.

This study builds on prior research into shape variations, focusing on waving defects in both industrial and benchmark profiles. Most previous studies on shape variations have primarily analyzed and optimized the design based on the initial flow of the profile, either by balancing the front-end [1,2] or minimizing concavity [3]. However, none of these studies have examined the evolution of parameters throughout the entire billet extrusion process, which is critical for understanding and addressing waving defects. To the best of the authors' knowledge, only one

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previous study has specifically addressed waving defects in profile extrusion [4]. Unlike other well-documented extrusion defects [5], such as billet skin [6,7], welding issues [8,9], underfilling [10], or those related to microstructure [11-13], the investigation of waving defects in profiles of industrial complexity has received limited attention, highlighting the need for further exploration in this area.

Using QForm UK software, full-billet simulations were conducted to analyse velocity and temperature evolution during the extrusion process. The analysis revealed that waving defects often originate from design-related factors, such as non-optimal feeder plate geometries or central feeding mechanisms, as well as process-related factors, such as inappropriate billet discard lengths. Benchmark simulations employing Arbitrary Lagrangian-Eulerian (ALE) methods were also used to investigate the subtle geometric influences on wave formation [4], further enhancing the understanding of these defects.

**Description of the case studies**

This study utilised three distinct projects to effectively identify and analyse the various root causes of the waving defect. The process parameters and geometrical details for all the investigated cases are summarised in Table 1.

*Table 1 – Technological and geometrical parameters of the investigated processes*

| Parameter | Units | Case 1 | Case 2 | Case 3 |
|---|---|---|---|---|
| Alloy | – | AA 6063 | AA 6063 | AA 6061 |
| Extrusion ratio | – | 83.38 | 41.19 | 32.54 |
| Container temperature | [°C] | 440 | 450 | 425 |
| Billet temperature | [°C] | 510 | 450 | 490 |
| Tool temperature | [°C] | 470 | 440 | 460 |
| Ram velocity | [mm/s] | 24 | 6 | 4.5 |
| Billet length | [mm] | 400 | 850 | 700 |
| Container diameter | [mm] | 100 | 279 | 210 |

The extrusion simulations were conducted using standard hot AA 6063 and AA 6061 alloys, readily available in the QForm UK material database. The coefficients of the Hensel-Spittel Eq. 1 for these materials [7], used in the simulations, are presented in Table 2.

$$\sigma_s = A \cdot e^{m_1 T} \cdot T^{m_9} \cdot \varepsilon^{m_2} \cdot e^{m_4/\varepsilon} \cdot (1+\varepsilon)^{m_5 T} \cdot \varepsilon^{m_7 \varepsilon} \cdot \dot{\varepsilon}^{m_3} \cdot \dot{\varepsilon}^{m_8 T}, \quad (1)$$

*Table 2 – Hensel-Spittel parameters for AA 6063 and AA 6061*

| Parameter | AA 6063 | AA 6061 |
|---|---|---|
| A | 265 | 219.5 |
| $m_1$ | -0.00458 | -0.00455 |
| $m_2$ | -0.12712 | -0.14576 |
| $m_3$ | 0.12 | 0.13 |
| $m_4$ | -0.0161 | -0.01357 |
| $m_5$ | 0.00026 | 0.0003 |
| $m_7$ | 0 | 0 |
| $m_8$ | 0 | 0 |
| $m_9$ | 0 | 0 |

Benchmark solid section. The authors of the work [4] studied the effects of a controlled flow imbalance on extrusion outcomes. This imbalance was intentionally introduced by designing a

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special feeder with a variable feeding area, causing aluminium to flow faster in the central region of the section. The feeder design was chosen to allow different flow conditions and identify the combination of parameters that could produce a wave.

In study [4], a 1.2 mm-thick strip made of AA 6063 alloy was extruded using various feeder designs (Fig.1), all with consistent 0.5 mm bearings. Only cases that were experimentally tested there were simulated in this study: feeder thicknesses ($W_{thick}$) of 21 mm, 27 mm, 33 mm, and 49.2 mm. Process parameters and geometrical details are provided in Table 1: Case 1.

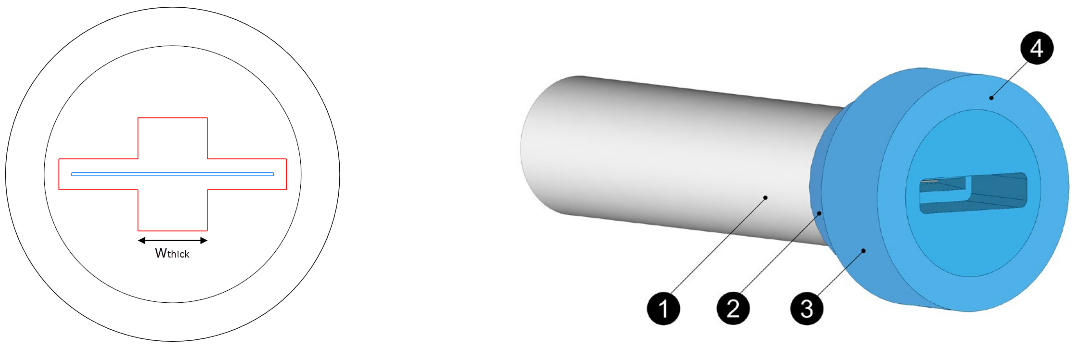


*Figure 1 – Base contours (left) and QForm UK setup (right): 1 – billet, 2 – die set, 3 – bolsters, 4 – pressure ring*

Industrial hollow section. The second investigation focused on an industrial hollow profile made of AA 6063 alloy, produced using a complex porthole design with central feeding (Fig. 2). This project specifically addressed the central feeding configuration, as such designs are generally associated with increased heat generation in the centre over time compared to the peripheral zones of the profile. This imbalance can potentially contribute to waving issues, making it an important area of study. Process parameters and geometrical details are provided in Table 1: Case 2.

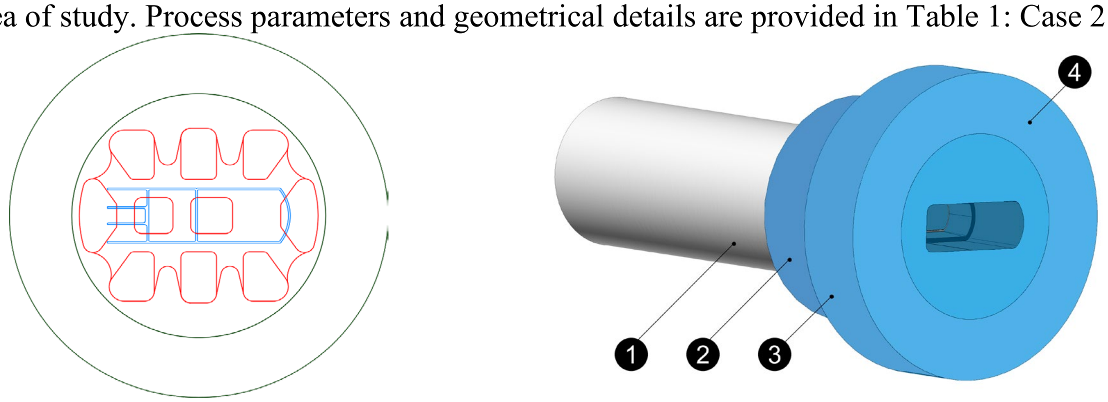


*Figure 2 – Base contours (left) and QForm UK setup (right): 1 – billet, 2 – die set, 3 – bolsters, 4 – pressure ring*

Industrial solid section. The third analysis focused on an L-type solid industrial profile with varying thicknesses, made from AA 6061 alloy and produced using a flat die with a feeder (Fig. 3). While for the first solid profile the tool was specifically designed to induce a wave for research purposes, in this case, the wave emerged as an actual manufacturing defect, impacting the overall process performance and productivity. Process parameters and geometrical details for this project are provided in Table 1: Case 3.

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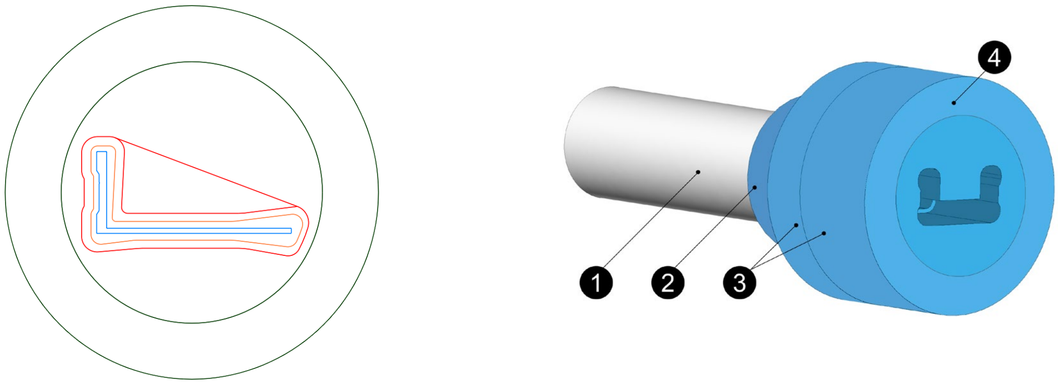



*Figure 3 – Base contours (left) and QForm UK setup (right): 1 – billet, 2 – die set, 3 – bolsters, 4 – pressure ring*

**Results and discussion**

Benchmark solid section. Four simulations were conducted for this project, testing different thicknesses of the central part of the feeder (Fig. 4): A – 21 mm, B – 27 mm, C – 33 mm, and D – 49.2 mm. As reported in [4], waving occurred only in case B (Fig. 5a), which aligns perfectly with the simulation results. Although no visible waving was observed in case C, a comparison of the velocity Y plots along the symmetry plane (Fig. 5b) shows a slight deviation above and below zero, as indicated by the blue line. This suggests that case C is operating near the conditions where the defect could potentially still occur.

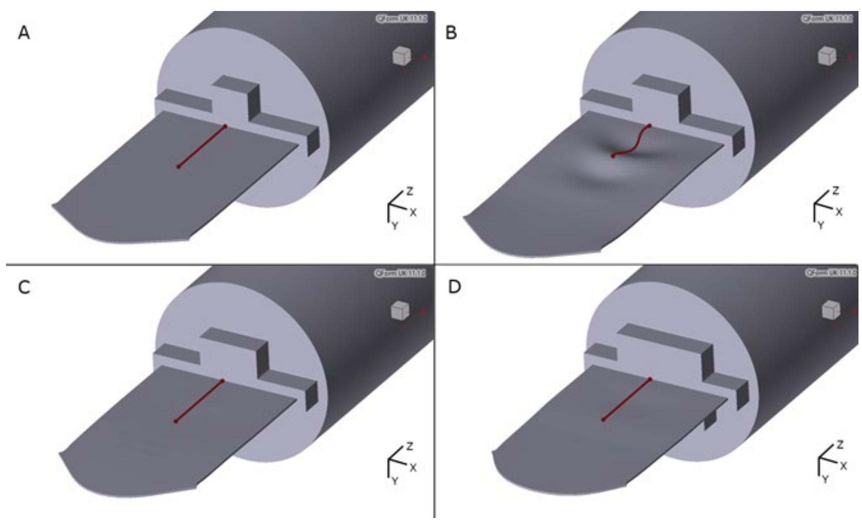
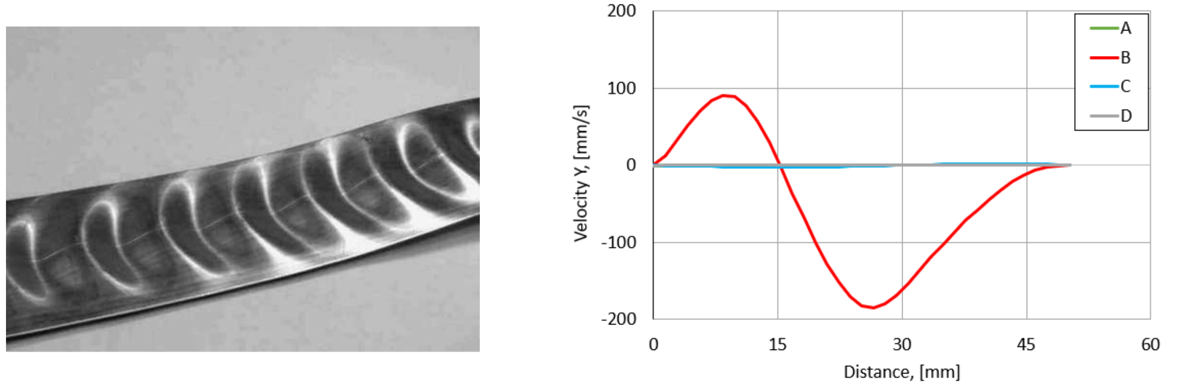



*Figure 4 – Comparison of simulation results for different geometries of the feeder. The dark red lines indicate the measuring distance.*

In this instance, the defect is definitely caused by the significant difference in feeding, leading to velocity variations between the central and peripheral regions. Importantly, this defect can be effectively avoided by using simulation to balance the front-end of the profile before production by adjusting the shape of the feeder, prechamber and bearings.




*a* *b*

*Figure 5 – a – experimental result from [4] when waving occurred; b – the plot of velocity Y along measuring lines indicated on Fig. 4*

Industrial hollow section. In this case the defect (Fig. 6) was developed during the intermediate stage of the process, even though the front-end remained well-balanced.

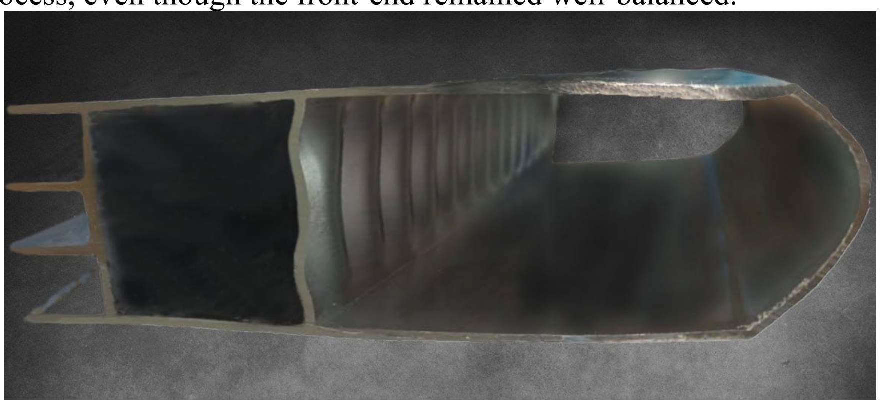


*Figure 6 – Profile with waving defect*

To investigate this issue, the entire billet was simulated using QForm UK Extrusion. The simulation revealed that, although the central profile wall initially exhibited an average velocity, it became the fastest part of the profile as the process progressed (Fig. 7, right). This acceleration occurred because the central region ($P_2$) experienced significantly higher heat generation compared to the surrounding areas (Fig. 7, left).

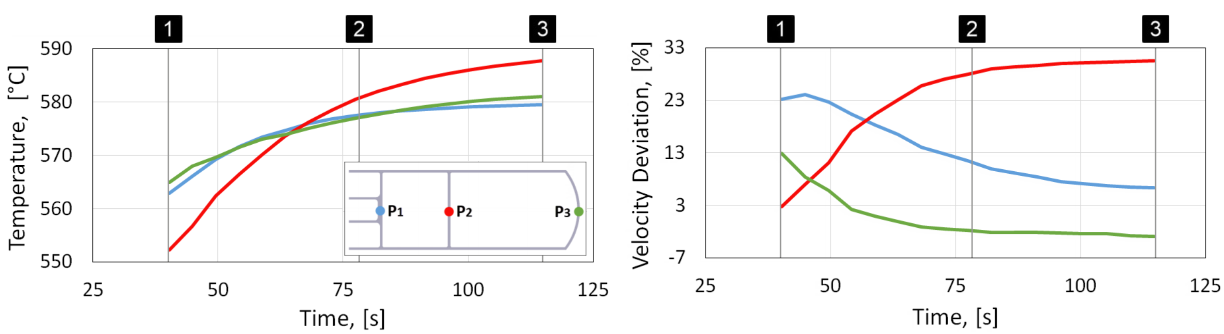



*Figure 7 – Temperature (left) and velocity deviation (right) evolution for different parts of the profile over time. 1, 2 and 3 indicate different stages of billet extrusion (Fig. 8)*

Since the design featured central feeding, meaning the central part of the profile was fed independently, the temperature increase caused more material to flow through this region. Without direct interaction with the slower-flowing ports, the system was unable to balance the flow rate. Consequently, the profile began to wave as it adjusted to maintain volume constancy.

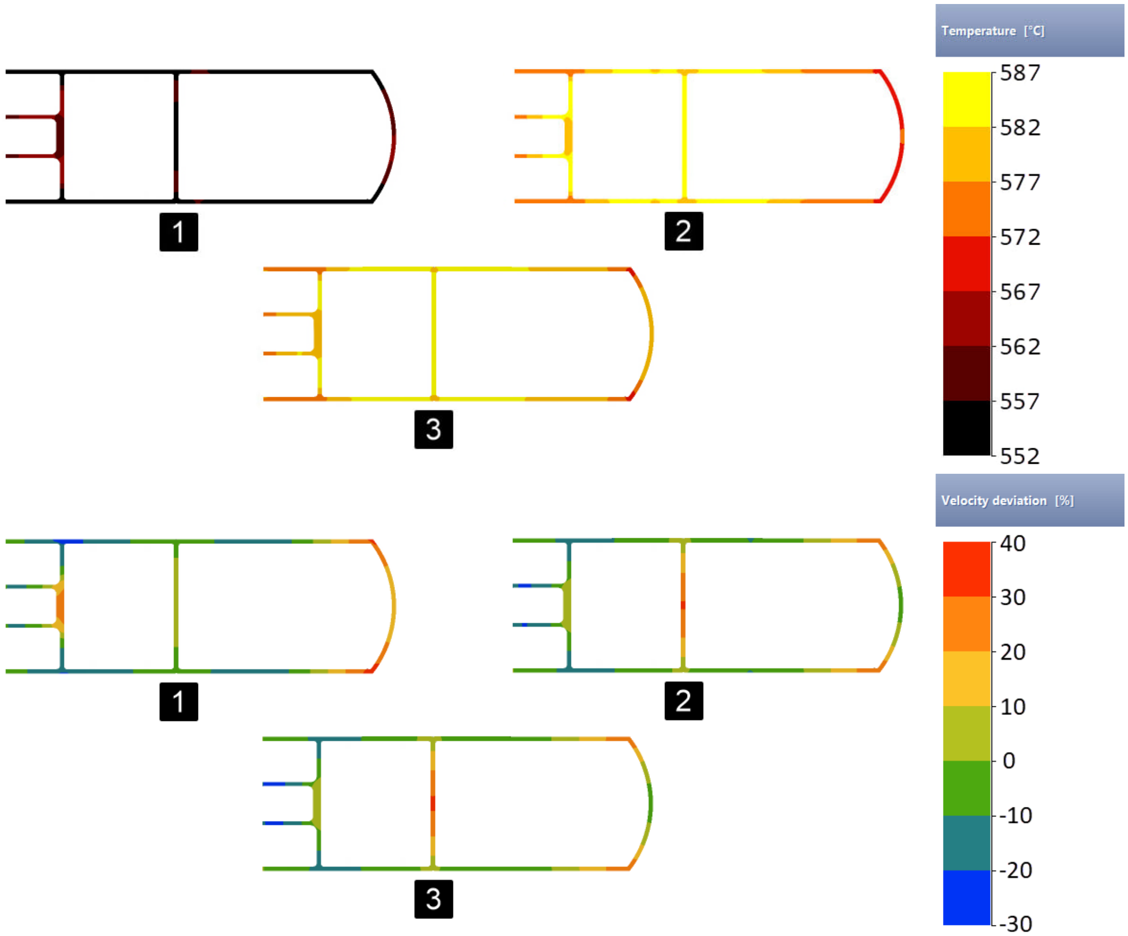



*Figure 8 – Temperature (top) and velocity deviation (bottom) evolution over time during the billet extrusion process (Fig. 7): 1 – beginning, 2 – intermediate, 3 – end*

Fig. 8 illustrates how temperature and velocity deviations evolve within the profile section at different stages of the extrusion process. Due to the high ratio of container area to profile area in extrusion processes, even a short stroke of the ram corresponds to a significant profile length being pushed. Capturing the evolution of temperature and velocity during the entire billet extrusion and consequently animating the waving defect within the profile would require simulating at least several meters of extruded material. This approach would generate an enormous number of finite elements and excessively long simulation times, making it impractical for industrial applications.

To address this challenge, the current study proposes a post-analysis method that enables the prediction of waving defects by focusing solely on the exit section of the profile throughout the entire billet extrusion process. Among the case studies conducted in this work, the longest simulation required approximately 4 hours. While this approach does not provide direct visualization of the wave formation in the simulation, it offers a practical and efficient way to prevent the defect.

Several techniques are commonly employed to address waving issues in cases similar to the one examined in this study. One approach involves shortening the feeding section of the mandrel, thereby reducing the length of intensive heat generation. Another method focuses on initially slowing down the central region, creating a greater velocity deviation at the start but compensating for it later as the central region warms up and accelerates.

These methods can help achieve a defect-free result when combined with optimised initial system temperatures. Alternatively, designing the tool to avoid central feeding can also be effective. However, in this scenario, precise control of dimensional tolerances is essential, as it may increase the lateral deflection of the mandrel cores.

Industrial solid profile. In this case, the defect appeared at the end of the billet extrusion process (Fig. 9) and occurred again at the end of the cycle for every subsequent billet. Unlike the previous case, temperature did not play a critical role in forming the defect in this instance, as it gradually decreased throughout the process for the entire profile (Fig. 10, left).

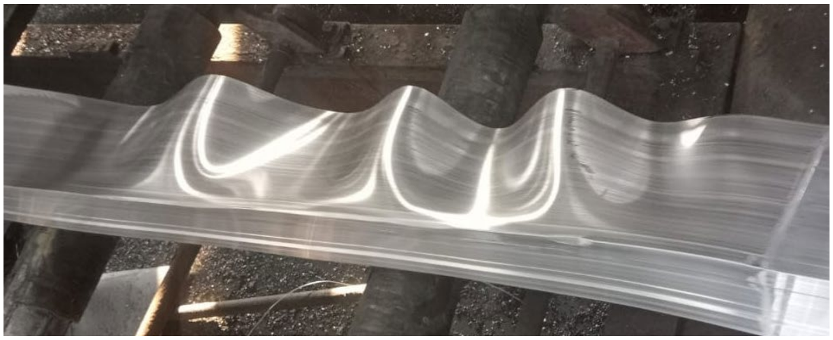


*Figure 9 – Profile with waving defect at the end of the extrusion cycle*

The simulation demonstrated that velocities remained nearly perfectly balanced until the final stage of the process, when the thinner region accelerated to 40% above the average profile velocity (Fig. 10, right).

The increase in velocity occurred as the billet zone under the ram entered the main deformation area, restricting the metal's ability to redistribute freely. Consequently, the metal began to flow into the feeder more uniformly.

Initially, the feeder design ensured balanced flow across the entire section, with the central feeder part supplying the thinner profile section and the lateral part feeding the thicker one. However, as the ram approached the final discard length of the billet, the uniform metal push into the feeder caused a significant increase in the flow through the central feeder section.

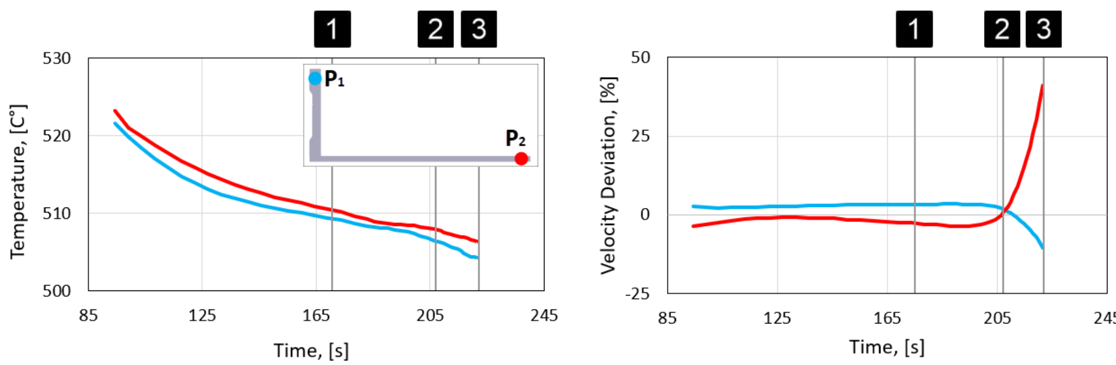



*Figure 10 – Temperature (left) and velocity deviation (right) evolution for different parts of the profile over time*

As shown in Table 3, the flow distribution through the feeder remained consistent until approximately 90 mm of the billet's remaining length. Beyond this point, significant changes in flow distribution emerged, leading to notable differences in profile velocity and ultimately causing the waving defect.

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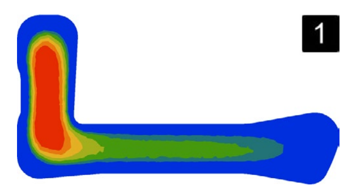
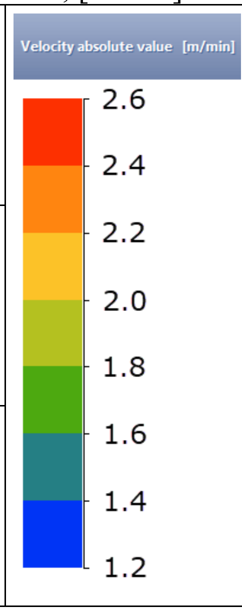
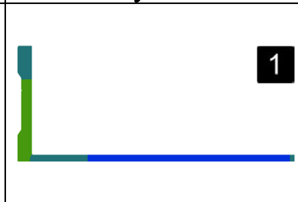
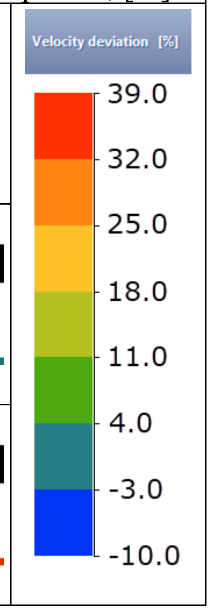
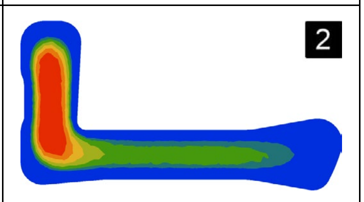
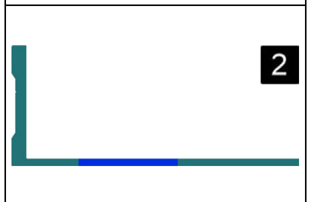
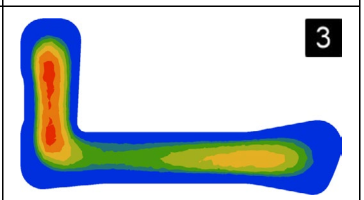
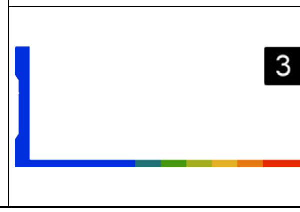
*Table 3 – Velocity distribution in the feeder and profile at various discard lengths (DL), corresponding to different stages of the billet extrusion process (Fig. 10)*

| DL, [mm] | Absolute velocity in feeder, [m/min] | | Velocity deviation in profile, [%] | |
|---|---|---|---|---|
| 225 |   |   |   |   |
| 90 |   | |   | |
| 35 |   | |   | |

In this scenario, increasing the discard length could potentially mitigate the issue, however, it would come at the cost of reduced productivity due to the shorter effective billet length. A more versatile and efficient solution would involve redesigning the tool, including the feeder and bearings, to achieve a balanced flow during the final stage of the extrusion process.

**Conclusions and practical recommendations**

This study aimed to simulate the extrusion processes of various industrial and benchmarking profiles to identify and understand the root causes of waving defects. Utilising the QForm UK software, three distinct scenarios leading to waving were effectively demonstrated through a comparative analysis of practical results and simulation outcomes:

- The primary and most evident root cause of the waving defect is an initial flow imbalance resulting from suboptimal tool design.
- Flow imbalance does not necessarily manifest at the start of the extrusion process but can develop during the intermediate stages as temperature distribution undergoes significant changes. This is particularly common in designs utilising central feeding, where isolated sections of the profile experience considerable heating, leading to flow acceleration and subsequent waving.
- Inappropriate billet discard length is another factor contributing to the waving defect. When combined with specific tool designs, this can cause significant velocity variations toward the end of the extrusion process, ultimately resulting in waving.

It is important to note, as highlighted in this study, that accurately predicting waving defects often necessitates simulating the entire billet. Simulations focusing solely on analysing the initial flow pattern may overlook hidden defects which appear at later stages of extrusion, as demonstrated in case studies 2 and 3.

As a summary, the presented research allows us to draw the following practical recommendations to avoid waving:

- Optimise tool geometry before running the actual trial:
  Initial flow should exclude significant velocity imbalance.
- Control central feeding dynamics:

Slowing down the central region at the beginning of the process can compensate for the increased velocity caused by higher temperatures later. This strategy requires some experience to understand the optimal values of the initial flow imbalance.

- Reduce heat generation zones:
  Shortening the mandrel's feeding part effectively reduces heat generation, particularly in the central regions, lowering the probability of defects.
- Refine initial process parameters:
  Adjusting the initial temperatures of the billet and tooling system can play a pivotal role in balancing material flow and mitigating velocity deviations throughout the process.
- Avoid central feeding in certain cases:
  In scenarios where dimensional tolerances can be tightly controlled, alternative feeding strategies that avoid central feeding may help reduce waving. However, careful consideration of potential lateral deflection is required to maintain profile accuracy.
- Leverage advanced simulation tools:
  Utilizing simulation software to model the entire extrusion process provides valuable insights into material flow and defect mechanisms. Regular validation of these models with experimental data is essential for process reliability.
- Monitor all the stages of extrusion process:
  As velocity and flow distribution changes are more pronounced during the intermediate and final stages of the extrusion process, implementing adaptive controls or adjustments in real time can help maintain defect-free profiles.
- Use an iterative design approach:
  Adopting an iterative approach to tool design, informed by simulation and experimental feedback, allows for continuous improvements in process efficiency and defect mitigation.

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