Finite Element-Based Optimization of a Porthole Die for an AA6063 Carrier Panel Profile under Radially Expanding Material Flow

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Unlike conventional aluminum extrusion profiles, the AA6063 carrier panel profile investigated in this study has a circumscribing circle diameter (CCD) larger than the billet diameter, resulting in an uncommon radially expanding material flow during porthole die extrusion. This unique flow condition considerably increases the difficulty of achieving uniform distributions of material flow, temperature, and strain. To overcome these challenges, finite element analyses were performed using Altair Inspire Extrude Metal 2022.2, and the die geometry was optimized through two successive design iterations until uniform material flow, temperature, and strain distributions satisfying industrial production requirements were achieved. The flow imbalance was reduced from approximately 60% in the initial design to about 5% in the optimized configuration. In addition, the required extrusion load was decreased by approximately 8%. The optimized die was successfully validated through industrial extrusion trials, showing excellent agreement with numerical predictions. The proposed methodology provides a practical design framework for complex hollow profiles exhibiting radially expanding material flow.

Keywords: *Porthole Die, Hollow Profile, AA6063, FEM, Flow Velocity.*

1. INTRODUCTION

Aluminum alloys are extensively used in various engineering sectors, particularly in automotive components, railway systems, aerospace structures, and architectural applications. Beyond these fields, aluminum also serves as a key material in a wide range of industrial and consumer products, including thin foils, pharmaceutical and food packaging, beverage containers, toothpaste tubes, and coatings for welding electrodes. Among various manufacturing processes, hot extrusion is one of the most efficient methods for producing aluminum profiles with high dimensional accuracy and excellent mechanical properties. In particular, extrusion through porthole dies is widely employed for manufacturing hollow and geometrically complex profiles owing to its high productivity, design flexibility, and capability to produce intricate cross-sectional geometries [1].

Porthole die extrusion is a hot extrusion process primarily used to manufacture hollow or multi-cell aluminum and magnesium profiles. This technique enables the production of complex geometries such as tubes, box sections, heat sinks, and structural components in a single extrusion pass while maintaining high dimensional accuracy and superior surface quality. In porthole die extrusion, the mandrel is not directly supported by external tooling; instead, it is held in position by several bridges that divide the material flow into multiple channels, referred to as portholes. As the billet material flows through these channels, it separates and subsequently rejoins within the welding chamber, where solid-state welding occurs under elevated temperature and pressure. The quality of the seam weld formed in this region directly determines the mechanical performance and structural integrity of the extruded profile. Consequently, achieving balanced material flow within the die is one of the most critical requirements for successful porthole die design [2,3].

Despite considerable advances in die manufacturing technologies, newly designed porthole dies generally require several trial-and-error modifications before an acceptable profile can be produced. These repeated die corrections increase both production costs and development time, making die optimization an important research topic for both academia and industry [4]. With the rapid development of computational technologies, finite element method (FEM) simulations have become one of the most effective tools for analyzing material flow behaviour and supporting die design optimization before costly industrial trials. Previous studies on porthole die extrusion can generally be classified into three main categories: (i) die geometry optimization, (ii) material flow prediction and balancing, and (iii) seam weld formation together with the associated microstructural evolution.

Regarding die geometry optimization, He et al. [5] and Engelhardt et al. [6] conducted a series of experimental and finite element studies investigating the influence of die pockets, die modifications, material flow behaviour, and die deformation, thereby establishing a fundamental methodological framework for porthole die design. Liu et al. [7] performed finite element simulations using HyperXtrude (ALE) to investigate conventional porthole die problems for an aluminum profile

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with a high length-to-width ratio and a small cavity. Three die modifications were proposed, resulting in improved flow balance and reduced die deformation. Truong et al. [8] presented a porthole die design metho–dology for complex solid heatsink profiles and demon–strated through finite element simulations that modi–fications to porthole geometry, pocket dimensions, bea–ring lengths, and bridge chamfers significantly improve flow uniformity. Similarly, Ayer et al. [9] optimized the bridge geometry of an AA6063 box profile using HyperXtrude and showed that curved bridge designs provide more favourable extrusion conditions and better flow uniformity. More recently, Özmen and Altınbalık [10] proposed a design modification for porthole dies used in consecutive billet extrusion to eliminate material accumulation during billet transition, while Ayer and Karakaya [11] presented practical design criteria to overcome welding-related problems during the extru–sion of AA6082 hollow profiles.

In addition to die geometry optimization, consi–derable research has focused on predicting and cont–rolling material flow during porthole die extrusion. Wang et al. [12] investigated the influence of bridge geometry and welding chamber configuration on flow behaviour, weld seam quality, and dimensional stability, demonstrating the direct effect of bridge design on process performance. Khan et al. [13] combined experimental observations with DEFORM-3D simula–tions to evaluate the influence of different porthole sizes on metal flow characteristics, while Xue et al. [14] investigated metal flow balancing in multi-output port–hole dies and demonstrated that advanced port configu–rations, bridge geometries, and welding chamber designs significantly improve flow uniformity. Hrudkina and Aliieva [15] investigated cold extru–sion processes using kinematic trapezoidal modules and demonstrated that appropriate combinations of kine–matic modules can be used to describe complex metal-flow patterns and optimize the relative velocity of mate–rial flow. Similarly, Aliieva et al. [16] analysed com–bined three-direction extrusion using an upper-bound power approach and evaluated the prevailing metal-flow direction through comparisons with finite element and experimental results, highlighting the importance of accurately characterizing material-flow behaviour in complex extrusion processes.

Another important research direction concerns seam-weld formation and the associated microstructural evolution during extrusion. Liu et al. [17] investigated the influence of billet temperature and ram speed on the mic–rostructure and mechanical properties of AA6005 alumi–num alloy near the welding region. Zang et al. [18] exa–mined the relationship between crystallographic texture and local plastic deformation at extrusion seam welds in an Al-Mg-Si alloy, whereas Viswanath et al. [19] per–formed combined numerical and experimental investi–gations on AA6063 porthole die extrusion, sho–wing that the number of portholes significantly influen–ces weld chamber conditions, extrusion load, and weld strength.

Although previous studies have provided valuable insights into porthole die design, material flow control, and process optimization, their applicability has mainly been demonstrated for conventional profile geometries and relatively predictable material-flow conditions. Consequently, these approaches may not be directly applicable to profiles involving substantial radial mate–rial expansion, where maintaining uniform material flow velocity, temperature distribution, and strain beco–mes more challenging. A distinctive feature of the car–rier panel profile investigated in this study is that its circumscribing circle diameter (CCD) exceeds the billet diameter. This non-conventional flow behaviour consi–derably increases the difficulty of achieving simul–taneous uniformity of material flow velocity, tempe–rature distribution, and strain throughout the profile, thereby making die design substantially more chal–lenging. To the best of the authors' knowledge, finite element-based optimization studies addressing this specific geometric characteristic have received very limited attention in the literature.

Motivated by this research gap, the present study aims to optimize the porthole die of a newly designed AA6063 carrier panel profile using finite element ana–lyses performed with Altair Inspire Extrude Metal 2022.2. Unlike previous studies that primarily focused on individual process variables, the proposed optimi–zation strategy simultaneously evaluates material flow velocity, temperature distribution, and strain evolution, since these three parameters collectively determine ext–rusion quality and die performance. The die design was systematically optimized through two successive design iterations until balanced thermo-mechanical conditions suitable for industrial production were achieved. Fi–nally, the optimized die design was validated through industrial extrusion trials, and excellent agreement was obtained between the numerical predictions and the manufactured profiles.Therefore, the present study not only demonstrates an effective finite element-based optimization methodology for porthole dies operating under radially expanding material flow conditions but also provides practical design guidance for reducing industrial trial-and-error, production time, and manu–facturing costs in the extrusion of complex hollow aluminum profiles.

2. MATERIALS AND METHODS

2.1 Porthole Dies

Porthole dies—also known as bridge dies—are com–monly used in the extrusion of aluminum and other non-ferrous alloys, especially for producing hollow profiles such as tubes, frames, and other complex profiles. They function by mechanically splitting and subsequently rejoining the metal flow in the welding chamber. A typical porthole die consists of three key elements:

Bridges: They separate the incoming metal flow into multiple streams.
Welding chamber: After splitting, the metal flows into this chamber and the metal streams are rejoined under high pressure and temperature.
Mandrel and shaping section: After solid-state wel–ding, the unified metal flow passes through the final shaping section to achieve the required profile dimensions.

2.2 Selection of the Carrier Panel Profile

The carrier panel profile investigated in this study was selected because it represents a particularly challenging extrusion case. Unlike conventional aluminum extrusion profiles, its circumscribing circle diameter (CCD) is larger than the billet diameter. Consequently, instead of the converging material flow commonly encountered in extrusion processes, the material is forced to expand radially while passing through the porthole die. This non-conventional flow condition considerably increases the difficulty of achieving uniform material flow, tem–perature distribution, and strain throughout the profile, making it an ideal case for finite element-based die optimization.The profile was selected based on the following criteria:

- It represents a new completely industrial product that had not previously been manufactured by the collaborating company.
- Its complex geometry and radially expanding mate–rial flow present a challenging die-design problem.
- The optimized die would be used for actual indus–trial production, allowing direct validation of the numerical predictions through manufacturing trials.

Finite element analyses were performed using Altair Inspire Extrude Metal 2022.2, a commercial software package widely employed for aluminum extrusion die design and process optimization and extensively vali–dated for industrial extrusion simulations [20]. The die optimization was carried out through the simultaneous evaluation of three key process parameters: material flow velocity, temperature distribution, and strain, which were considered the primary indicators of extrusion performance and die design quality.

2.3 Material Selection

AA6063 is a heat-treatable Al–Mg–Si (6xxx series) wrought aluminum alloy widely used in the extrusion industry because of its excellent extrudability, good corrosion resistance, high surface quality, and balanced mechanical properties. These characteristics make it particularly suitable for manufacturing hollow profiles with complex cross-sectional geometries and have established AA6063 as one of the most commonly used alloys for architectural, transportation, and general engineering applications.

Due to its stable flow behaviour and reliable seam weld formation during porthole die extrusion, AA6063 has become a reference material for both industrial app–lications and finite element-based die design studies. Whalen et al. [1] investigated the re-extrusion of AA6063 chips through a porthole die using the Shear Assisted Processing and Extrusion (ShAPE) process and demon–strated successful metallurgical bonding within the welding chamber. Tang [21] studied the co-extrusion of AA6063/AA7075 aluminum alloys using a porthole die and reported stable material flow together with satis–factory weld quality. Additional studies have likewise confirmed the suitability of AA6063 for manufacturing hollow profiles by porthole die extrusion [22,23].

Considering its widespread industrial use, stable extrusion characteristics, and extensive validation in previous studies, AA6063 was selected as the billet material for the present investigation. The chemical composition of the alloy is listed in Table 1.

Table 1. Chemical composition of AA6063 alloy (%wt)

Fe	Si	Cu	Mn	Mg
0.35	0.20-0.60	0.10	0.10	0.45-0.90
Zn	Cr	Ti	Al	
0.10	<0.10	0.15	Balance	

3. ANALYSIS PROCESS

The profile investigated in this study is a carrier panel profile specifically selected because it represents a non-conventional extrusion condition. Unlike conventional hollow profiles, its circumscribing circle diameter (CCD) exceeds the billet diameter, requiring the mate–rial to expand radially during extrusion. This geometric characteristic significantly increases the complexity of die design and makes the achievement of balanced material flow considerably more difficult.

As illustrated in Figure 1, the profile has an overall width of 294 mm, whereas the billet container diameter of the intended extrusion press is 215 mm. Conse–quently, the material must be redistributed over a consi–derably larger cross-sectional area than thatencountered in conventional extrusion processes. Furthermore, the profile incorporates 13 bridge outlets, each of which must receive a balanced supply of material to ensure uniform flow conditions.

The combination of the large profile dimensions and multiple bridges is expected to generate significant va–riations in material flow velocity between the central and peripheral regions of the die. These velocity differences may lead to non-uniform wall thicknesses, dimensional inaccuracies, and an increased risk of bridge deformation due to uneven loading, ultimately reducing die service life. Therefore, material flow velocity was considered the primary design criterion during die optimization, while temperature distribution and strain were simultaneously evaluated to ensure stable thermo-mechanical conditions throughout the extrusion process.

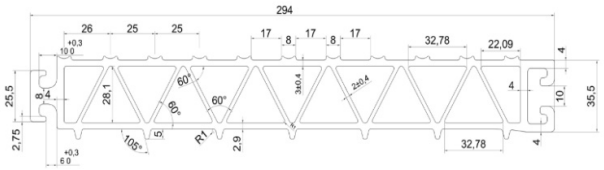


Figure 1. Geometry and dimensions of the profile

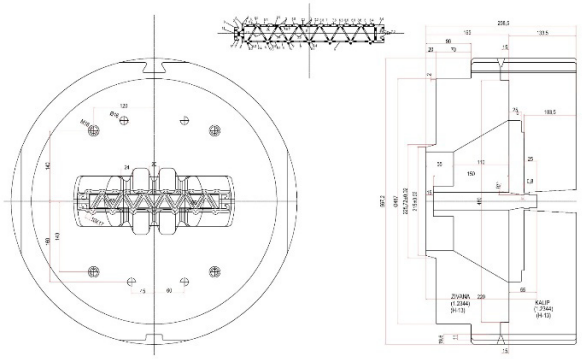


Figure 2. Initial design and dimensions of the carrier panel profile die

To achieve the desired geometry, the die design was carried out by following the procedures comprehen–sively described in the literature [20]. The corresponding technical drawing and dimensions are also presented in Figure 2. For a clearer visualization of the die configu–ration, the disassembled 3D CAD model of the porthole die is presented in Figure 3. The mandrel and die plate are shown separately, highlighting the port–holes, bridges, and mandrel bearing on the mandrel, as well as the wel–ding chamber, die bearing, and pocket on the die plate.

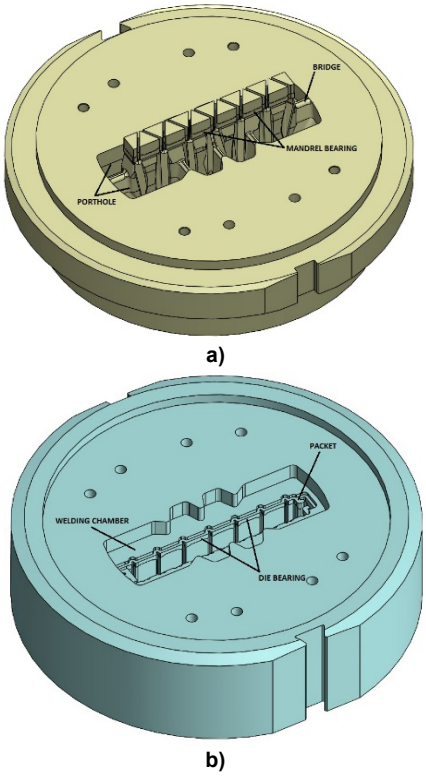


Figure 3. Example of disassembled porthole die of the carrier panel profile a) mandrel and b) die plate

For the detailed analysis of the profile illustrated in Figure 2, the following input parameters were entered into the simulation software.

Material: AA6063

- Billet Temperature: 450°C
- Ram Speed: 4 mm/s
- Container Temperature: 420°C
- Container Diameter: 212 mm
- Heat transfer coefficient: 3000 W/m^{2}K

The billet was discretized using TET4 elements with an average element edge length of 13.16 mm, whereas the die/tooling was discretized using a combination of TET4 and PRISM6 elements with an average element edge length of 1.34 mm. A fine mesh was employed, resulting in a total of 3,776,258 elements and 1,261,332 nodes, including 2,366,058 tetrahedral elements and 1,410,200 triangular prism elements. The Viscoplastic friction model was applied at the aluminum–die interface, with a friction coefficient of 0.30

Initial Material Flow Velocity Distribution

Material flow velocity is the primary design parameter in porthole die optimization because it directly governs dimensional accuracy, wall thickness uniformity, and seam weld quality. Therefore, the initial die design was first evaluated in terms of the exit velocity distribution, as illustrated in Figure 4.The initial design exhibits a pronounced non-uniformity in the exit velocity distribution. As shown in Figure 4, the difference bet–ween the highest and lowest material flow velocities is approximately 60%, indicating a severe flow imbalance across the profile. This behaviour is mainly attributed to the large profile dimensions relative to the billet dia–meter and the presence of 13 bridge outlets, which make balanced material feeding considerably more challen–ging. For satisfactory industrial production, the velocity variation between regions having identical wall thick–nesses should preferably remain below approximately 20%. The results obtained from the initial design clearly exceed this acceptable range, indicating that substantial die modifications are required to achieve balanced material flow before industrial production.

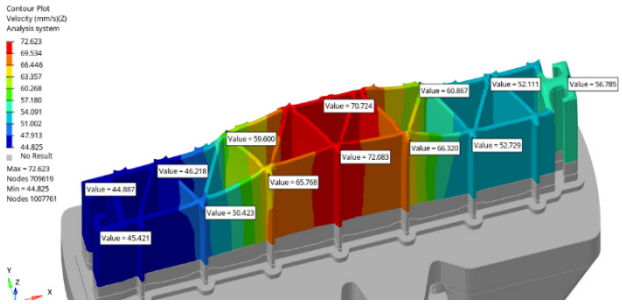


Figure 4. Exit velocity distribution of initial die design of the carrier panel

3.2. Initial Temperature Distribution

Following the evaluation of material flow velocity, the temperature distribution at the profile exit was analyzed because temperature is another key factor governing metal flow behaviour, seam weld formation, and pro–duct quality during porthole die extrusion. The tempe–rature distribution predicted for the initial die design is presented in Figure 5.As shown in Figure 5, the maximum exit temperature reaches approximately 541 °C in the central region of the profile, whereas the edge regions exhibit temperatures of approximately 509 °C, corresponding to a temperature difference of about 6.5%. This non-uniform thermal distribution is consis–tent with the material flow imbalance observed in the velocity analysis.

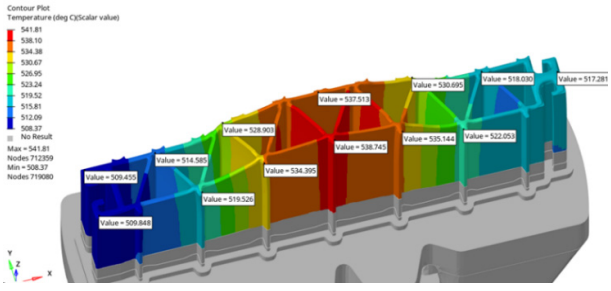


Figure 5. Exit temperature distribution of initial die design of the carrier panel

Since the profile contains significant variations in wall thickness, such temperature differences may adver–sely influence seam weld integrity, dimensional stability,

and the overall quality of the extruded profile. Consequently, the temperature analysis further confirms that the initial die design requires optimization to obtain a more uniform thermo-mechanical state during extrusion.

4. DIE DESIGN REVISIONS AND EVALUATION

The analyses of the initial die design revealed a pronounced imbalance in material flow, with approximately 60% variation in exit velocity between the central and peripheral regions of the profile. This imbalance was primarily attributed to the non-conventional profile geometry, whose circumscribing circle diameter exceeds the billet diameter, together with the presence of 13 bridge outlets requiring balanced material feeding. Consequently, die geometry modifications were undertaken to improve material distribution and reduce the velocity differences observed in the initial design.

The first design revision focused on improving material feeding to the edge regions of the profile. In the initial design, the geometry of the angled die bridges located near the profile ends provided insufficient inlet area, restricting material flow in these regions. Conversely, the central sections, owing to their larger feeding areas and shorter flow paths from the die center, received excessive material, resulting in considerably higher exit velocities. To overcome this imbalance, the inlet sections of the angled cavities located at the boundary of the hub diameter (Figure 6) were extended by 5 mm toward the die center and provided with an additional inclination, thereby increasing the effective feeding area. This modification was intended to promote material flow toward the profile ends while simultaneously reducing excessive flow concentration in the central region. The revised die geometry is illustrated in Figure 6.

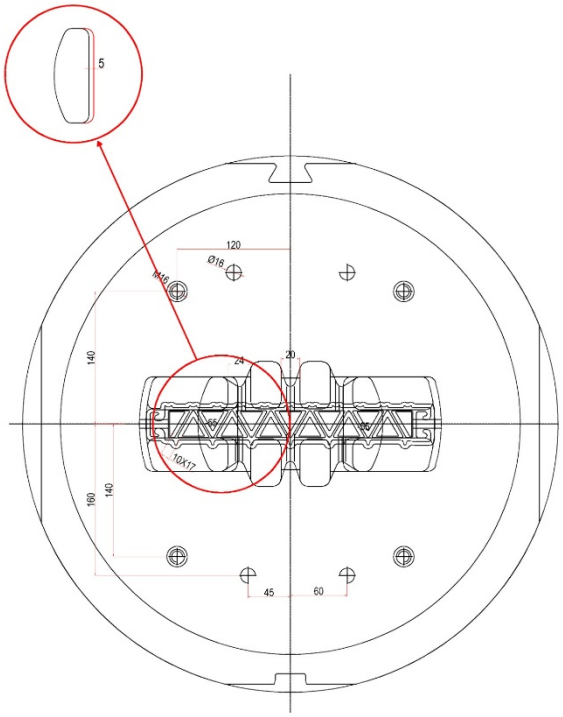


Figure 6. Revised design of the carrier panel profile die

After the die design was revised as described above, the analysis was repeated to evaluate the resulting changes in exit velocity distribution changed, and the results are presented in Figure 7.

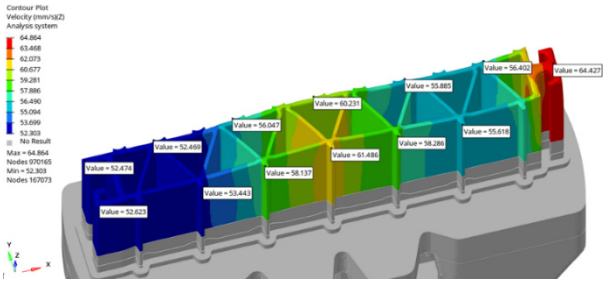


Figure 7. Exit velocity distribution of the revised die design of carrier panel

Following the first die design revision, the exit velocity distribution was re-evaluated to assess the effectiveness of the implemented modifications. The corresponding velocity distribution is presented in Figure 7. Compared with the initial design, the average velocity difference between the low-velocity (blue) and high-velocity (red) regions was significantly reduced from approximately 60% to 20%, demonstrating that the first revision substantially improved material flow balance. As shown in Figure 7, the maximum exit velocity of 64.4 mm/s occurs in the red region, which corresponds to a section having a relatively larger wall thickness than the surrounding areas. Therefore, this local increase in velocity was considered acceptable from the viewpoint of extrusion performance. Nevertheless, the approximately 17% velocity difference remaining between the blue and yellow regions indicates that homogeneous material flow had not yet been fully achieved. Since these regions possess similar wall thicknesses, their exit velocities are also expected to be similar. Consequently, reducing the velocity difference in these regions to below 10% was established as the objective of the second design revision.

To achieve this objective, an additional modification was introduced to the four porthole cavities feeding the central region of the profile. In the previous design, each cavity had a cross-sectional area of 1542 mm². By reducing the opening dimensions by 4 mm, the area of each cavity was decreased to 1414 mm², thereby restricting material flow toward the central region and promoting a more balanced distribution of material toward the profile edges.The updated die configuration following the second design revision and the corresponding modified region are illustrated in Figure 8.To provide a clearer three-dimensional representation of the geometric modification, the corresponding regions of the die before and after the second design revision are presented in Figure 9. The comparison clearly illustrates the reduction in the four porthole cavity openings from 1542 mm² to 1414 mm². The modified regions are highlighted in different colors to facilitate direct visualization of the change in the die geometry.

Following the second revision, the analyses for exit velocity and temperature distribution were repeated, and the results are presented in Figures 10 and 11, respectively.

The exit velocity distribution after the second die design revision is presented in Figure 10. The results indicate that the velocity differences between regions

with identical wall thicknesses were reduced to approximately 5%, demonstrating that the target of achieving balanced material flow had been successfully accomplished. Therefore, the second revision was considered to provide a satisfactory die design for industrial production.

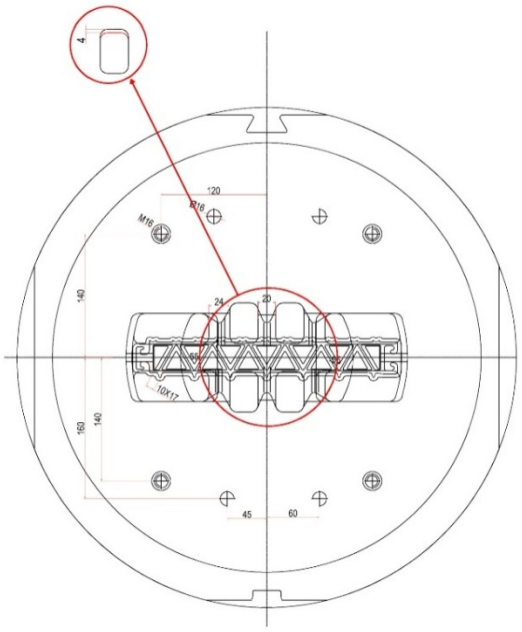
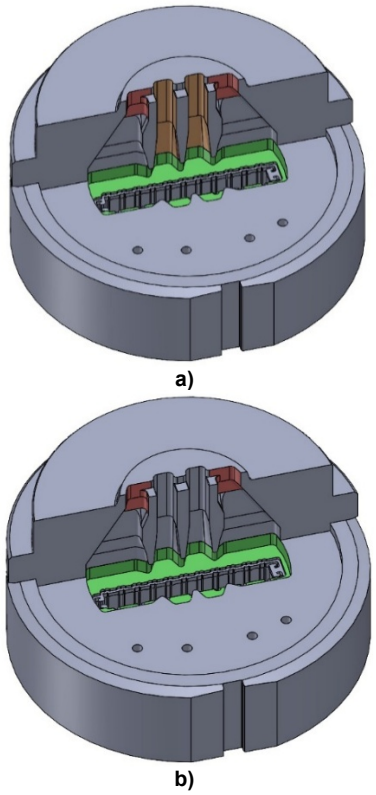


Figure 8. Second revised design and final dimensions of the carrier panel profile die



a)

b)

Figure 9. Three-dimensional representation of the die geometry before and after the second design revision: a) porthole cavities with a cross-sectional area of 1542 mm² before modification, and b) modified porthole cavities with a cross-sectional area of 1414 mm² after modification.

Following the successful optimization of the material flow, the exit temperature distribution was reevaluated. The corresponding temperature field is shown in Figure 11. The maximum exit temperature in the central region is approximately 534 °C, whereas the temperatures at the profile edges range between 509 °C and 515 °C. Compared with the initial design, the temperature difference was reduced from approximately 6.5% to 5%. Considering the non-conventional profile geometry, whose circumscribing circle diameter exceeds the billet diameter, together with the flow-balancing channels introduced during the optimization process, this temperature distribution was considered acceptable for the extrusion process.

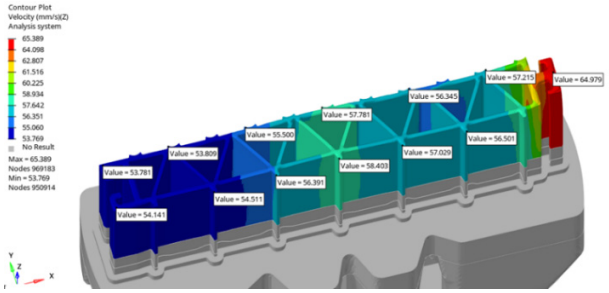


Figure 10. Exit velocity distribution of the second revised die design of carrier panel

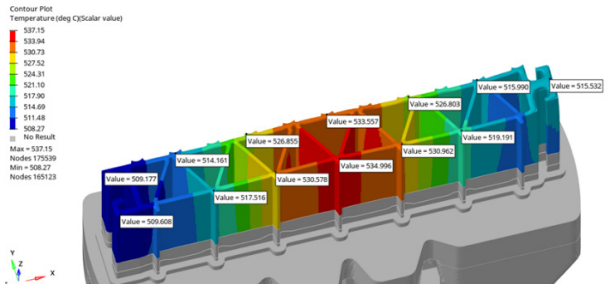


Figure 11. Exit temperature distribution of the second revised die design of carrier panel

Since the optimized die design satisfied the target criteria for both material flow velocity and temperature distribution, the final evaluation parameter was selected as the strain distribution. The strain fields obtained from the initial design and the second revised design are presented in Figures 12.a and 12.b, respectively.As expected, relatively high strain values occur in regions where the material is redirected through the feeding channels and subjected to intense plastic deformation. In particular, the profile ends exhibit the highest strain levels owing to the severe compression experienced during material redistribution. As illustrated in Figure 12.a, the initial die design produces a markedly non-uniform strain distribution, with differences reaching approximately 30% between the central and edge regions. After the second revision (Figure 12.b), the reduction in material flow toward the central region promoted a more balanced redistribution of material across the profile. Consequently, although the average strain increased by approximately 38%, its spatial distribution became significantly more homogeneous, indicating a more stable deformation behaviour throughout the extrusion process.

Following the completion of the second die design revision, the optimized die geometry was considered suitable for manufacturing. Prior to production, the required extrusion load was calculated to verify that the designed die could be operated within the capacity of the intended extrusion press.

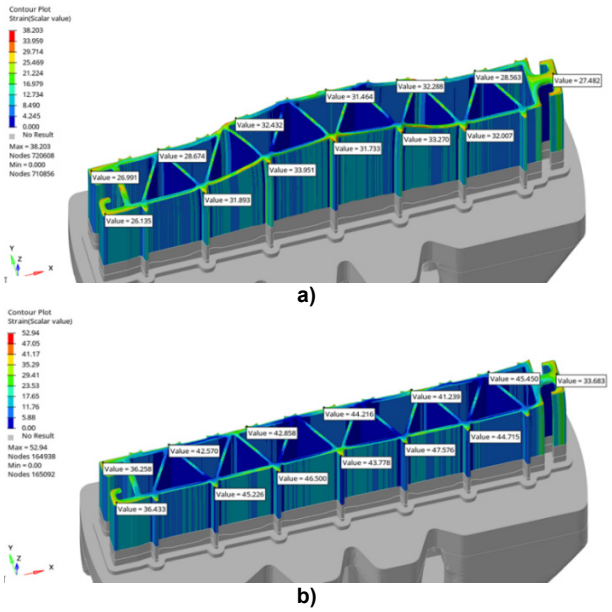


Figure 12. Strain distribution of carrier panel a) Initial design b) Second revised design

For comparison purposes, the extrusion loads predicted for the initial die design and the second revised design were evaluated under identical process conditions. The corresponding load curves are presented in Figure 13. As can be observed, the initial die design requires a higher extrusion load throughout the forming process. In contrast, the optimized die not only provides improved material flow and a more uniform temperature distribution but also significantly reduces the required extrusion load.

The calculated extrusion load decreased by approximately 8%, corresponding to a reduction of nearly 100 tons relative to the initial design. This reduction can be attributed to the improved material flow achieved through the optimized die geometry, which minimized localized flow resistance and promoted a more uniform deformation of the billet. This reduction represents an important practical advantage, as it decreases the mec–hanical load imposed on the extrusion system while improving process efficiency.Since the extrusion loads predicted for the first and second revised designs were found to be very similar, only the results of the initial and second revised designs are presented in Figure 13 for clarity.

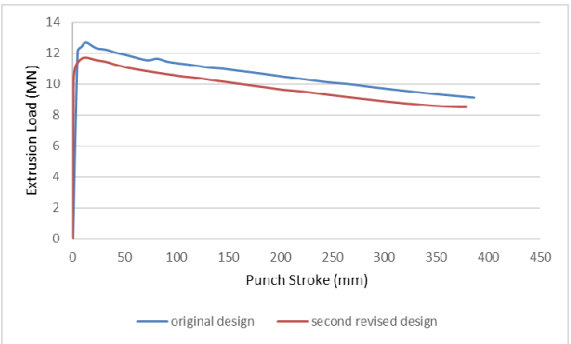


Figure 13. Comparison of the load values versus punch stroke

5. EXTRUSION OF THE FINAL PRODUCT

Following the completion of the die design optimization, the revised die was manufactured and used to extrude the carrier panel profile from AA6063 aluminum alloy. As shown in Figure 14, the final profile was successfully produced with a high-quality surface and without any visible welding defects. The dimensional accuracy of the extruded profile was quantitatively evaluated using dimensional inspection data obtained from the final profile. A total of 109 dimensional characteristics were inspected, comprising 104 linear dimensions and five angular dimensions. For the linear dimensions, all 104 measurements were within the specified dimensional acceptance criterion of ±0.40 mm relative to the nominal dimensions, corresponding to a 100% dimensional conformity rate. The deviations of the linear dimensions ranged from −0.36 to +0.37 mm, with a mean deviation of +0.029 mm, a mean absolute deviation of 0.140 mm, and a standard deviation of 0.167 mm. The five measured angular dimensions were also within their specified ±1° tolerance. A statistical summary of the linear dimensional inspection results, including the number of dimensions evaluated, acceptance criterion, conformity rate, deviation limits, mean deviation, mean absolute deviation, and standard deviation, is presented in Table 2. These results quantitatively confirm that the extruded profile met the specified dimensional requirements.



Figure 14. Extruded profile of the final product of carrier panel

Table 2. Statistical evaluation of the linear dimensional accuracy of the extruded profile

Statistical Result	Value
Number of linear dimensions	104
Acceptance criterion	±0.40 mm
Within tolerance	104 / 104 (100%)
Maximum positive deviation	+0.37 mm
Maximum negative deviation	−0.36 mm
Maximum absolute deviation	0.37 mm
Mean deviation	+0.029 mm
Mean absolute deviation	0.140 mm
Standard deviation	0.167 mm

The successful production of the profile confirms the validity of the finite element-based die design methodology adopted in this study. The optimized die geo–

metry provided balanced material flow, acceptable temperature distribution, and stable deformation conditions during extrusion, resulting in a product that satisfied the expected industrial production requirements. The agreement between the numerical predictions and the experimental production demonstrates that the proposed two-stage die optimization strategy can effectively support the design of porthole dies for geometrically challenging hollow aluminum profiles.

6. CONCLUSION

This study presented a finite element-based optimization methodology for the design of a porthole die used in the extrusion of an AA6063 carrier panel profile characterized by a non-conventional material flow condition. Unlike conventional hollow aluminum profiles, the investigated profile possesses a circumscribing circle diameter (CCD) larger than the billet diameter, requiring the material to expand radially during extrusion. This unique geometric characteristic considerably increases the complexity of die design and makes achieving balanced material flow more difficult.

The initial die design exhibited a material flow velocity variation of approximately 60% between the central and peripheral regions of the profile. To overcome this imbalance, the die geometry was systematically optimized through two successive design iterations. The first revision, involving the enlargement of the feeding regions at the profile ends, reduced the velocity variation to approximately 20%. A second revision, achieved by reducing the cross-sectional area of the four central porthole cavities from 1542 mm² to 1414 mm², further decreased the velocity difference to approximately 5% in regions with identical wall thicknesses, resulting in a well-balanced material flow suitable for industrial production.

The improvements in material flow were accompanied by significant improvements in the thermo-mechanical behaviour of the extrusion process. The temperature distribution became considerably more uniform while remaining within the acceptable industrial extrusion range, confirming that the optimized die geometry effectively minimized the thermal imbalance observed in the initial design.

Although the average strain increased due to the redesigned feeding channels, its distribution became substantially more homogeneous throughout the profile, indicating a more stable deformation behaviour during extrusion. Furthermore, the optimized die reduced the required extrusion load by approximately 8% (about 100 tons), demonstrating that improved material flow not only enhanced product quality but also improved process efficiency by reducing the mechanical load on the extrusion system.

The optimized die was subsequently manufactured and successfully validated through industrial extrusion trials. The excellent agreement between the finite element predictions and the produced carrier panel profile confirms the reliability of the proposed optimization methodology and demonstrates the capability of numerical simulations to substantially reduce conventional trial-and-error die corrections during porthole die development.

Overall, the present study demonstrates that the simultaneous evaluation of material flow velocity, temperature distribution, and strain provides a robust and practical framework for porthole die optimization. The successful industrial validation confirms the reliability of the proposed finite element-based iterative design methodology and demonstrates its capability to substantially reduce conventional trial-and-error die corrections. Therefore, the proposed approach provides practical guidance for shortening die development time, reducing manufacturing costs, minimizing die correction cycles, and improving product quality in industrial aluminum extrusion.

From an industrial perspective, the proposed optimization approach can be directly applied to the development of porthole dies for complex hollow aluminum profiles. By identifying and correcting non-uniform material flow, temperature, and strain distributions before manufacturing the final die, the proposed methodology can reduce the need for repeated trial-and-error die modifications, thereby shortening die development time and reducing associated manufacturing costs. The approach is particularly applicable to profiles with unconventional cross-sectional geometries and radial material expansion, for which conventional die-design experience may not provide sufficient guidance. The successful validation through industrial extrusion trials further demonstrates the practical applicability of the proposed FEM-based methodology for supporting production-oriented die design and improving the reliability of complex aluminum profile manufacturing.

Future research may extend the proposed methodology to other complex porthole-die geometries with different ratios between the profile circumscribing circle diameter and billet diameter. Further studies could investigate the combined effects of additional process and die-design parameters, such as billet temperature, ram speed, die temperature, friction conditions, bearing lengths, and welding chamber geometry, through multi-objective optimization approaches. Experimental investigations involving a wider range of profile geometries and extrusion conditions would further contribute to the development of generalized design guidelines for porthole dies operating under non-conventional material-flow conditions.

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ОПТИМИЗАЦИЈА МАТРИЦЕ СА КАНАЛИМА (ТИП „PORTHOLE") ЗА AA6063 ПРОФИЛ НОСЕЋЕГ ПАНЕЛА ПРИМЕНОМ МЕТОДЕ КОНАЧНИХ ЕЛЕМЕНАТА У УСЛОВИМА РАДИЈАЛНОГ ШИРЕЊА ТОКА МАТЕРИЈАЛА

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За разлику од уобичајених алуминијумских профила добијених екструзијом, профил носећег панела од легуре AA6063, који је предмет овог истраживања, има пречник описаног круга (CCD) већи од пречника блока, што доводи до неуобичајеног радијалног ширења тока материјала током екструзије кроз матрицу са каналима. Овакви јединствени услови тока значајно отежавају постизање равномерне расподеле тока материјала, температуре и дефор–

мације. Ради превазилажења ових изазова, спро–ведене су анализе методом коначних елемената по–моћу софтвера Altair Inspire Extrude Metal 2022.2, а геометрија матрице је оптимизована кроз две узас–топне итерације дизајна све док нису постигнуте равномерне расподеле тока материјала, температуре и деформације које задовољавају захтеве индус–тријске производње. Неуједначеност тока је сма–њена са приближно 60% у почетном дизајну на око 5% у оптимизованој конфигурацији. Поред тога, потребна сила екструзије смањена је за око 8%. Оптимизована матрица је успешно верификована путем индустријских проба екструзије, показујући одлично слагање са нумеричким предвиђањима. Предложена методологија пружа практичан оквир за пројектовање сложених шупљих профила код којих долази до радијалног ширења тока материјала.