Key Engineering Materials
ISSN: 1662-9795, Vol. 1051, pp 125-133
doi:10.4028/p-rlVb3W

Submitted: 2026-01-18
Revised: 2026-02-16
Accepted: 2026-02-17
Online: 2026-04-17

Productivity and Quality Trade-Offs in Aluminum Extrusion: Towards Circularity Tolerant Process Windows

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Keywords: aluminum extrusion, process robustness, circular manufacturing, principal component analysis (PCA), multi-hole extrusion.

Abstract. Aluminum extrusion plays a critical role in lightweight structural applications and circular economy strategies. However, extrusion process design is constrained by competing objectives: increasing productivity through higher ram speeds or increased die-hole count improves throughput and material utilization yet simultaneously elevates force demand and defect susceptibility. In this work, a numerical statistical framework is proposed to identify circularity-tolerant process windows, defined as multi-objective design regions that balance productivity, product quality, and sustainability performance. A three-factor Taguchi design was employed to systematically vary ram speed, billet temperature, and die-hole count in the extrusion of AA6063. Twenty-seven full 3D thermo-mechanical extrusion simulations were conducted using the DEFORM finite element platform employing an Arrhenius-type constitutive model from literature. Key extrusion responses maximum ram force, local damage indicator, and total displacement were analyzed using Principal Component Analysis (PCA) to reveal correlations and trade-offs between productivity-oriented parameters and quality-related responses. The results demonstrate a clear divergence between productivity drivers (ram speed, die-hole count) and process capability indicators, providing quantitative evidence of the inherent productivity quality trade-off. The proposed framework enables the identification of robust extrusion operating regions suitable for circular manufacturing scenarios in aluminum extrusion. The proposed framework is particularly relevant for extrusion scenarios where process robustness must be ensured under increasing material and operational variability, such as those anticipated with higher recycled content.

Introduction

Aluminum extrusion is a cornerstone manufacturing process for lightweight structural components in transportation, construction, and energy applications, owing to its ability to produce complex cross-sections with high material utilization and excellent recyclability. Continuous industrial pressure to improve productivity has led to widespread adoption of higher ram speeds, increased extrusion ratios, and multi-hole die configurations, all of which enhance throughput and reduce billet discard [1]. However, these productivity-oriented strategies are inherently coupled with increased deformation severity, higher force demand, and elevated defect susceptibility, giving rise to fundamental productivity quality trade-offs.

These trade-offs have been extensively documented in both experimental and numerical studies. Increased ram speed and extrusion ratio have been shown to raise local strain rates and thermal gradients, thereby increasing the risk of surface cracking, internal damage, and flow instabilities [2], [3], [4]. Similarly, multi-hole dies, while attractive from a material efficiency perspective, introduce complex flow interactions that can amplify deformation heterogeneity and defect formation if not carefully controlled [5], [6], [7]. As a result, productivity enhancement in extrusion is rarely a monotonic improvement problem but rather a constrained multi-objective design challenge.

Aluminum is often cited as a “circular material” due to its recyclability; however, circularity at the process level depends not only on material choice but also on stable operation, low scrap generation

[8], and efficient use of energy and tooling [9], [10]. Defect-driven scrap, rework, and process instability directly undermine circularity by increasing remelting demand and energy consumption, regardless of whether primary or recycled feedstock is used. Consequently, circularity-oriented extrusion design must explicitly consider process robustness alongside productivity.

Despite this, most existing extrusion optimization studies remain focused on point-wise optima, often identified using Design of Experiments (DoE), response surface methods, or evolutionary algorithms [2], [11], [12]. While such approaches can identify parameter combinations that perform well under nominal conditions, they are inherently sensitive to operational variability and model uncertainty. Small deviations in ram speed, billet temperature, or friction conditions can shift the process outside the optimal region, leading to unstable operation and quality degradation. From an industrial perspective, such fragility limits the practical usefulness of point-based optimization.

Multivariate statistical methods offer a complementary perspective by emphasizing structure and robustness rather than isolated optima. PCA, in particular, has been successfully applied in manufacturing to identify dominant modes of variation, uncover correlations among responses, and reduce dimensionality in complex process datasets [11], [13], [14]. In metal forming applications, PCA has been shown to provide physically interpretable axes that reflect competing deformation, thermal, and force-related mechanisms [15]. However, its use in extrusion research has largely been confined to post-hoc analysis or process monitoring, rather than as a tool for process window identification.

Building on this foundation [16], the present study systematically characterizes productivity–quality trade-offs in aluminum extrusion by reframing process design around circularity-tolerant process windows rather than single optimal parameter sets. Circularity tolerance is interpreted at the process-system level, emphasizing operating regions that balance productivity and quality while remaining robust to realistic parameter variation.

Using three-dimensional finite element simulations of AA6063 extrusion and a structured Taguchi design, PCA is employed to reveal the dominant productivity–quality trade-offs governing process behavior. Stable operating regions in reduced PCA space are then identified as candidate process windows suitable for robust and circularity-oriented operation.

By shifting the focus from optimization to trade-off management and robustness, this study provides a framework that complements existing optimization approaches and aligns extrusion process design with practical industrial and circular manufacturing objectives.

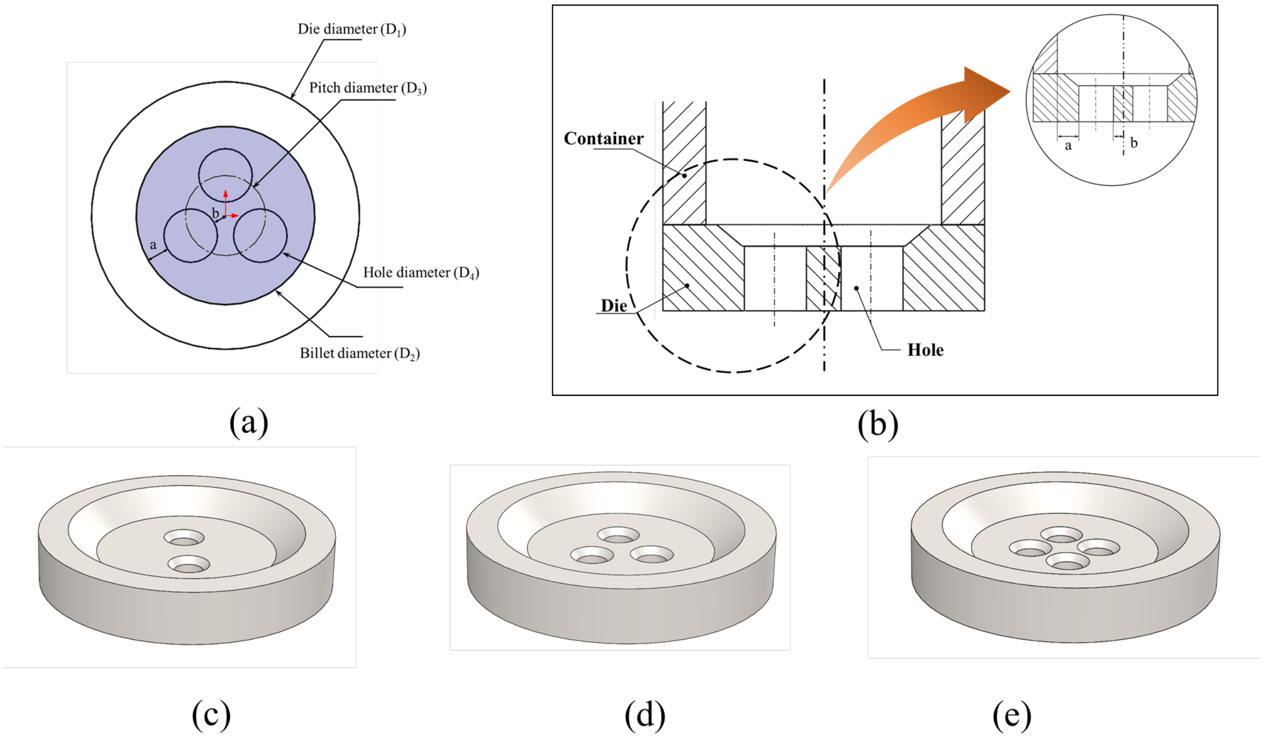
In mature industrial extrusion operations, the majority of material losses are typically associated with structural process scrap such as butt ends, start-up skin contamination, and cutting logistics related to profile length, rather than instability-driven defects. These losses are largely independent of process parameter fluctuations and are commonly addressed through production planning and downstream handling strategies. Consequently, conventional single-point process parameter settings, determined through trimming trials and subsequently fixed for production, are generally sufficient to ensure stable operation under narrowly controlled alloy specifications. However, the ongoing transition towards increased use of recycled and mixed-scrap billet feedstocks is expected to introduce greater batch-to-batch variability in material behaviour, which challenges the robustness of such single-point settings. Under these conditions, process instability may re-emerge as a relevant contributor to non-process scrap, motivating the need for systematic approaches that explicitly account for robustness under variability rather than optimization under nominal conditions.

Methodology

Die Geometry and Hole Configuration

The die configurations investigated consisted of 2, 3, and 4 hole layouts arranged symmetrically with respect to the billet center Figure 1 (c-e). In the 2-hole configuration, holes were positioned diametrically opposite at 180° spacing. The 3-hole configuration employed equal angular spacing of 120°, while the 4-hole configuration used 90° spacing. The holes were distributed along a constant pitch circle diameter of approximately 11 mm, derived from an eccentricity ratio of 0.3 to minimize outlet bending and flow imbalance.

All configurations were designed to maintain geometric symmetry in order to eliminate artificial flow non-uniformity arising purely from layout asymmetry. Increasing the number of holes modifies the extrusion ratio (32, 21.3, and 16 for 2, 3, and 4 hole dies, respectively), thereby influencing material velocity gradients, hydrostatic stress distribution, and damage evolution during extrusion. These geometric effects are known to significantly affect flow balance and quality metrics in multi-hole extrusion processes.



(a) (b)

(c) (d) (e)

Fig. 1. Geometric configuration of the investigated multi-hole extrusion dies. (a) Schematic definition of billet diameter D_2, pitch circle diameter D_3, hole diameter D_4, and eccentricity parameters. (b) Sectional view illustrating pocket geometry and bearing length used to control material flow. (c–e) Three-dimensional CAD representations of the 2-hole (180° spacing), 3-hole (120° spacing), and 4-hole (90° spacing) symmetric layouts, respectively.

Design of Experiments

In this work, circularity tolerance is interpreted at the process-system level as the ability of the extrusion process to maintain acceptable force demand, deformation behaviour, and damage levels in the presence of unavoidable variability. Rather than equating circularity exclusively with recycled material input, the present framework emphasises process robustness as a necessary precondition for circular manufacturing, particularly in scenarios where material properties cannot be assumed constant. Circularity-tolerant process windows are therefore defined as operating regions in which productivity- and quality-related responses remain balanced and resilient to perturbations, enabling stable operation without repeated re-trimming of process parameters.

A Taguchi L27 orthogonal array was employed to structure the numerical experiments, enabling efficient exploration of the design space with three factors at three levels each. The investigated parameters and their corresponding levels are summarized in Table 1.

Table 1. Taguchi L27 OA Factorial design.

Factors	**Levels**		
	Level 1	**Level 2**	**Level 3**
Number of holes (A)	2	3	4
Ram speed [mm/s] (B)	6	7	8
Extrusion temperature [°C] (C)	400	450	500

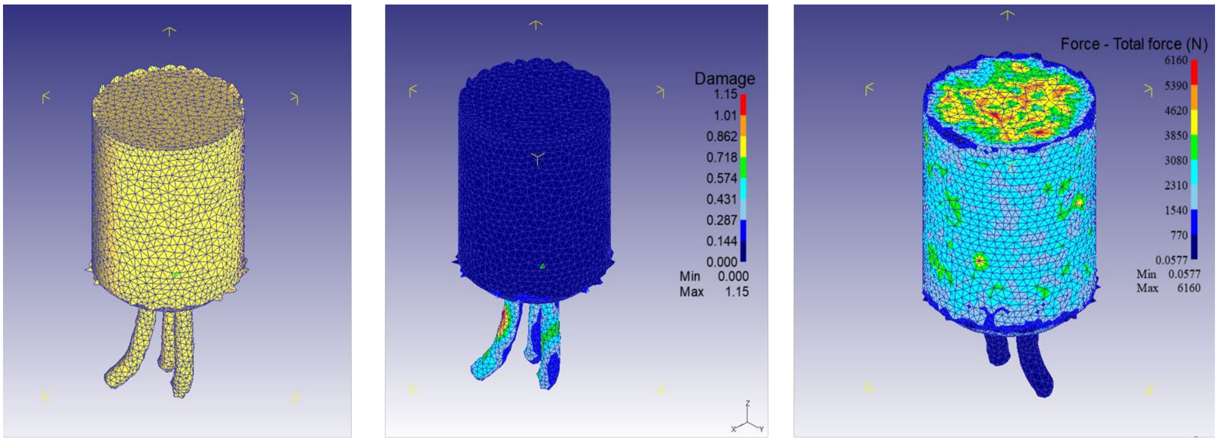
This design resulted in 27 extrusion simulations capturing interactions between productivity-driven and thermal parameters. The extrusion responses considered in the analysis were 1) maximum ram force, 2) maximum local damage, and 3) maximum total displacement.

These variables were selected to represent productivity-related effects, quality-related risks, and process feasibility constraints.

Numerical Model

Three-dimensional extrusion simulations were conducted using the commercial finite element software DEFORM. The extrusion of AA6063 was modeled under steady-state conditions using a rigid die and deformable billet formulation. The billet material behavior was described using an Arrhenius-type constitutive model, with parameters adopted from established literature sources [17]. The predicted ram force magnitudes and deformation patterns were consistent with published numerical and experimental extrusion studies under similar processing conditions.

The present investigation focuses on relative comparisons among die configurations using a consistent modeling framework. Therefore, the conclusions are based on comparative trends rather than absolute predictive accuracy.



(a) *(b)* *(c)*

Fig. 2. FEA model (a) mesh/ flow, (b) Damage and (c) Force.

For each simulation Figure 1, the following responses were extracted. Maximum ram force, local damage, and maximum total displacement; representing energy demand, defect susceptibility and material flow and deformation intensity respectively. These responses collectively characterize extrusion productivity, process capability, and quality risk.

In the present study, the built-in ductile damage indicator provided by the software was employed as a comparative measure of damage accumulation. This indicator is based on strain accumulation and stress-state evolution during deformation and is commonly used in extrusion studies to assess defect susceptibility under compressive dominant stress conditions.

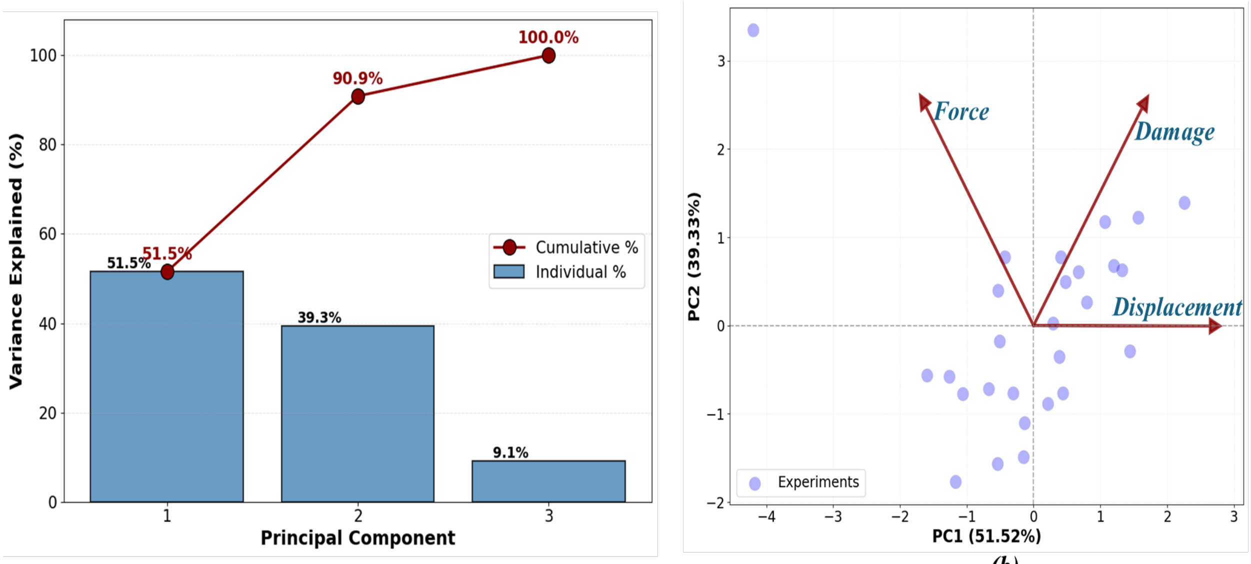
Multivariate Analysis

Principal component analysis was applied to the standardized response variables to reduce dimensionality and identify dominant correlations. PCA scores were used to locate individual extrusion runs in reduced space, while loading vectors were used to interpret the physical meaning of the principal components.

Results

Dominant Productivity–Quality Trade-off Structure

The scree plot Figure 2 (a) indicates that the first two principal components explain approximately PC1% ≈ 50–55% and PC2% ≈ 35–40% of the total variance, respectively, capturing approximately ~90% of the overall system variability.



(a) *(b)*

Fig. 3. PCA (a) Scree plot: Explained Variance by Principal Components (b) Biplot: Scores + Loadings (PC1–PC2).

Analysis of PCA loadings shows that Figure 2 (b) PC1 is dominated by deformation-related responses and productivity-linked effects, capturing the trade-off between throughput-enhancing measures and deformation severity. PC2 is dominated by maximum ram force, reflecting feasibility constraints imposed by press capacity and tooling limits. Together, PC1 and PC2 define a productivity–quality trade-off space, within which extrusion behavior can be systematically interpreted.

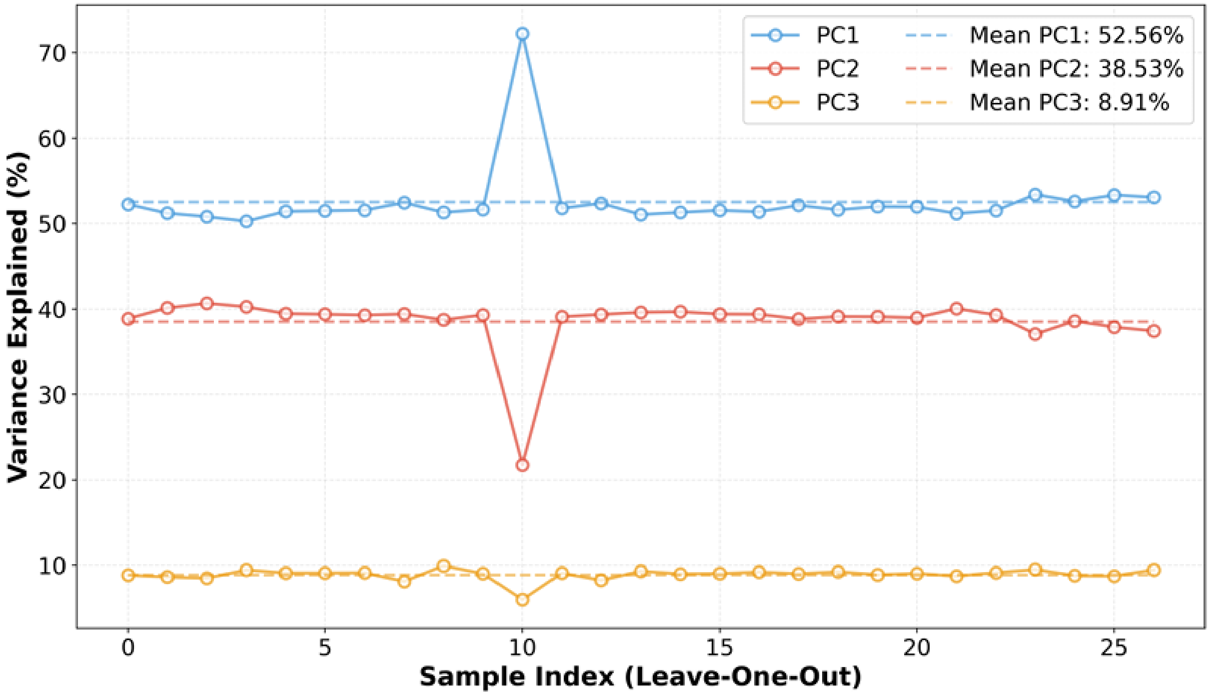


Fig. 4. Leave one out cross validation.

To assess the stability and generalizability of the PCA-derived process windows, Leave-One-Out Cross-Validation (LOOCV) was performed on the full dataset of 27 extrusion simulations. For each iteration, a single observation was excluded, the PCA model was refit on the remaining 26 samples, and variance explained by each principal component was recalculated.

The LOOCV analysis, depicted in Figure 3, demonstrates that PC1 and PC2 remain remarkably stable across all 27 leave-one-out iterations, with PC1 variance consistently clustering around the mean value of 52.56% and PC2 around the value of 38.53%. The singular perturbation at sample 10 (corresponding to the mid-range parameter combination) reflects the influence of a nominally central experimental point, yet this deviation is transient and does not propagate across the broader sample space. Importantly, PC3 remains negligible (8.91% mean variance) across all iterations, confirming that the two-component representation robustly captures the dominant process trade-offs regardless of which single observation is omitted.

This consistency validates that the identified circularity-tolerant process windows are not artifacts of specific outlying conditions but represent genuine structural features of the aluminum extrusion design space. The robustness of the PCA decomposition under LOOCV thus strengthens confidence in the practical applicability of the proposed framework for industrial process design.

Principal Components

The first principal component (PC1), accounting for approximately 51.5% of the total variance, is primarily associated with displacement and damage responses. This component therefore represents a productivity deformation severity axis, capturing the coupling between throughput enhancing parameters (e.g., increased hole count and ram speed) and the corresponding increase in deformation intensity and defect susceptibility.

The second principal component (PC2), explaining approximately 39.3% of the variance, is dominated by maximum ram force. PC2 can thus be interpreted as a feasibility axis, reflecting constraints imposed by press capacity and load requirements. While PC1 describes the trade-off between productivity and quality risk, PC2 governs whether a given operating condition remains mechanically viable.

Together, PC1 and PC2 define a physically interpretable productivity quality trade-off space. Operating points located within moderate PC1 and PC2 ranges correspond to balanced conditions where productivity gains do not induce excessive deformation severity or force escalation. This structure provides the basis for identifying circularity-tolerant process windows.

Identification of Circularity-Tolerant Process Windows

The biplot Figure 2 (b) illustrates the relationship between the three response variables damage, ram force, and displacement in the reduced PC1-PC2 space. The spatial distribution of experimental points reveals the trade-offs inherent in the extrusion process. Damage and displacement vectors point in relatively different directions, indicating they respond differently to process parameter changes, while ram force provides an intermediate response characteristic.

The circularity-tolerant process window is identified in the region where experiments cluster with moderate PC scores neither extreme in either direction. This central operating region represents a balance between productivity (minimized force and displacement) and quality (controlled damage), while demonstrating resilience to small parameter variations. The scattered distribution around the origin Figure 2 (b) suggests that realistic parameter deviations would keep the process performance within acceptable tolerances in this zone, making it the optimal circularity-tolerant window for aluminum extrusion. Operating within such windows reduces sensitivity to process fluctuations and supports stable, waste-minimizing extrusion practice.

From a circularity perspective, robustness is a critical enabler for material efficiency. Stable extrusion operation is a known enabler for reduced scrap, rework, and energy-intensive remelting, thereby supporting overall sustainability performance.

The proposed framework enables circularity-oriented process design by explicitly linking productivity–quality trade-offs to stable operating regions, rather than relying on fragile point-wise optima.

Conclusion

This study investigates productivity and quality trade-offs in aluminum extrusion through a multivariate analysis framework and introduces the concept of circularity-tolerant process windows. The key conclusions are:

- Aluminum extrusion behavior is governed by a dominant productivity–deformation trade-off and an orthogonal force feasibility constraint.
- Stable operating regions emerge in reduced PCA space, representing circularity-tolerant process windows.
- Identifying such windows is a necessary precursor to meaningful and robust process optimization.
- The proposed approach provides a systematic pathway toward robust and circularity-oriented extrusion process design.

While the present analysis assumes fixed constitutive properties for AA6063, the proposed framework remains applicable under moderate material variability typical of circular production environments, as such variations would primarily shift operating points within the identified PCA structure rather than alter its underlying trade-off relationships.

The present study does not explicitly model variations in billet chemistry or structural sources of process scrap such as butt length or cutting strategy, which are known to dominate material losses in mature industrial extrusion environments. Instead, it establishes a general framework for identifying robust operating regions under controlled material conditions. From an industrial perspective, the proposed approach is not intended to replace established trimming trials for stable alloy systems, but to complement them in scenarios where increasing feedstock variability, for example due to higher recycled content, undermines the reliability of conventional single-point parameter settings. In such contexts, pre-identified circularity-tolerant process windows may support faster stabilisation and controlled performance degradation rather than abrupt process instability.

Acknowledgement

Authors acknowledge financial support by the Horizon Europe Project "ZEVRA" (GA: 101138034).

References

[1] J. Hirsch, "Recent development in aluminium for automotive applications," Trans. Nonferrous Met. Soc. China, vol. 24, no. 7, pp. 1995–2002, Jul. 2014, doi: 10.1016/S1003-6326(14)63305-7.

[2] L. Li, J. Zhou, and J. Duszczyk, "Prediction of temperature evolution during the extrusion of 7075 aluminium alloy at various ram speeds by means of 3D FEM simulation," J. Mater. Process. Technol., vol. 145, no. 3, pp. 360–370, Feb. 2004, doi: 10.1016/J.JMATPROTEC.2003.09.003.

[3] T. Hatzenbichler and B. Buchmayr, "Finite element method simulation of internal defects in billet-to-billet extrusion," Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 224, no. 7, pp. 1029–1042, 2010, doi: 10.1243/09544054JEM1830.

[4] C. V. Nielsen, W. Zhang, L. M. Alves, N. Bay, and P. A. F. Martins, Modeling of Thermo-Electro-Mechanical Manufacturing Processes with Applications in Metal Forming and Resistance Welding, no. 9781447146421. 2013. [Online]. Available: https://doi.org/10.1007/978-1-4471-4643-8.

[5] X. Xue, G. Vincze, A. B. Pereira, J. Pan, and J. Liao, "Assessment of metal flow balance in multi-output porthole hot extrusion of AA6060 thin-walled profile," Metals (Basel)., vol. 8, no. 6, pp. 1–15, 2018, doi: 10.3390/met8060462.

[6] Y. Dong, C. Zhang, W. Luo, S. Yang, and G. Zhao, "Material flow analysis and extrusion die modifications for an irregular and multitooth aluminum alloy radiator," Int. J. Adv. Manuf. Technol., vol. 85, no. 5–8, pp. 1927–1935, 2016, doi: 10.1007/s00170-016-8666-5.

[7] F. K. Chen, W. C. Chuang, and S. Torng, "Finite element analysis of multi-hole extrusion of aluminum-alloy tubes," J. Mater. Process. Technol., vol. 201, no. 1–3, pp. 150–155, May 2008, doi: 10.1016/J.JMATPROTEC.2007.11.292.

[8] N. Jamali-Zghal, B. Lacarrière, and O. Le Corre, "Metallurgical recycling processes: Sustainability ratios and environmental performance assessment," Resour. Conserv. Recycl., vol. 97, pp. 66–75, Apr. 2015, doi: 10.1016/J.RESCONREC.2015.02.010.

[9] J. Allwood, "THE FUTURE IN PRACTICE Sustainable materials – with both eyes open Sustainable materials – with both eyes open," State Sustain. Leadersh., pp. 3–5, 2012.

[10] M. A. Reuter, "Limits of design for recycling and 'sustainability': A review," Waste and Biomass Valorization, vol. 2, no. 2, pp. 183–208, 2011, doi: 10.1007/s12649-010-9061-3.

[11] G. Zhao, H. Chen, C. Zhang, and Y. Guan, "Multiobjective optimization design of porthole extrusion die using Pareto-based genetic algorithm," Int. J. Adv. Manuf. Technol., vol. 69, no. 5–8, pp. 1547–1556, 2013, doi: 10.1007/s00170-013-5124-5.

[12] A. Wagiman, M. S. Mustapa, R. Asmawi, S. Shamsudin, M. A. Lajis, and Y. Mutoh, "A review on direct hot extrusion technique in recycling of aluminium chips," Int. J. Adv. Manuf. Technol., vol. 106, no. 1–2, pp. 641–653, 2020, doi: 10.1007/s00170-019-04629-7.

[13] I. T. Jollife and J. Cadima, "Principal component analysis: A review and recent developments," Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., vol. 374, no. 2065, 2016, doi: 10.1098/rsta.2015.0202.

[14] F. Westad, L. Lodgaard, and T. Pedersen, Data Pre-processing and Sensor-Fusion for Multivariate Statistical Process Control of an Extrusion Process, vol. 1, no. 1. Association for Computing Machinery, 2023. doi: 10.1145/3617573.3618029.

[15] T. de Souza and B. Rolfe, “Multivariate modelling of variability in sheet metal forming,” J. Mater. Process. Technol., vol. 203, no. 1–3, pp. 1–12, Jul. 2008, doi: 10.1016/J.JMATPROTEC.2007.09.075.

[16] Y. Solomon, D. K. Sinha, P. J. Ramulu, and S. S. Gautam, “Numerical Investigation of Product Capability and Enhancement Through Multi-hole Extrusion Process,” in Technology Innovation in Mechanical Engineering. Lecture Notes in Mechanical Engineering, https://link.springer.com, 2022, pp. 791–802. doi: 10.1007/978-981-16-7909-4_73.

[17] T. Zhou, C. Ke, and T. Chen, “Hot Deformation Behavior and Processing Map of 5356 Aluminum Alloy,” J. Phys. Conf. Ser., vol. 1838, no. 1, 2021, doi: 10.1088/1742-6596/1838/1/012023.