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Enhancing Gating System Efficiency in Plastic Die Extrusion Through Finite Element Mold Flow Simulation

Ankita Anil Pojge[1], D. P. Kharat[2], S. R. Shekokar[3], N. A. Kharche[4], Y. A. Kharche[5], C. R. Patil[6]

[1,2,3,4,5]*Department of Mechanical Engineering, Padmashri Dr. V.B. Kolte College of Engineering, Malkapur, Buldana, Maharashtra, India*

[6]*Professor, Department of Mechanical Engineering, PRMIT&R, Badnera-Amravati, Maharashtra, India*

Abstract: - The automotive industry has recently experienced a significant surge in the use of plastic materials. This shift, particularly evident in the move toward replacing heavier metal components with more intricate plastic alternatives, is driven by the industry's focus on developing lighter vehicles. In this study, Mold Flow Analysis (MFA) was utilized to identify the most efficient gate configuration for a plastic cladding component. To minimize warpage and enhance material flow during molding, a CAD-based mold flow simulation was conducted. The analysis compared two gating configurations—an 8-drop and a 6-drop system. Results indicated that the 8-drop setup led to higher levels of warpage, whereas the 6-drop system demonstrated better performance. Consequently, the mold was manufactured using the 6-drop gating design, and production was carried out using this optimized setup. The final part was evaluated using a specialized inspection device to ensure it met the dimensional and quality standards outlined in the technical drawings. Additionally, the component underwent physical validation to confirm its compliance with all design and performance requirements.

Keywords: *Automotive industry, Plastic components, Mold Flow Analysis (MFA), Gating system optimization, Warpage reduction, Injection molding, Design validation*

1. Introduction

Plastic cladding tools are a crucial part of modern manufacturing, as they allow for the production of components with high precision and long-lasting durability. In injection molding, accurately designing the gate—both in terms of number and location—is essential, since these factors directly influence how the material flows and ultimately affect the quality of the molded part. If the gating system is poorly configured, it can lead to common defects such as weld lines and warpage, which not only reduce part quality but also drive up production costs. Mold flow analysis helps solve these problems by simulating how the material flows and how heat is distributed during the molding process.

Studies have shown that mold flow simulations can be highly effective in optimizing gate design and improving overall part quality (Hwang and Kim, 2019; Wang et al., 2018). Research also confirms that proper gate positioning can enhance material flow and significantly reduce warpage (Li et al., 2007; Jamsheed et al., 2015). Recent technological developments have introduced advanced simulation tools that incorporate Taguchi methods, ANOVA, and machine learning, which have made mold flow analysis even more powerful (Oliaei et al., 2016; Huang et al., 2020). These modern techniques help fine-tune processing parameters to minimize warpage (Zhao et al., 2022; Shi et al., 2009). From a sustainability perspective, optimizing gate location also contributes to reducing energy consumption during manufacturing (Huszar et al., 2015). Still, as product geometries become more complex, continued research is needed to refine gating strategies.

This study focuses on optimizing the number of gates using mold flow analysis, with the aim of establishing clear guidelines for improving product quality and manufacturing efficiency. Injection molding remains vital in plastics production due to its capability to form complex shapes, and a wide range of thermoplastics can be used for this process. CAE tools such as Autodesk Moldflow Insight assist in mold design and validation [1]. Plastics also offer advantages over metals like steel, including lower weight and better manufacturing efficiency. One of the main defects in molded parts is warpage—a form of geometric distortion [3]—which can be corrected through design changes and simulation analysis using tools like Autodesk Moldflow Insight [2].

Issues such as warping and shrinkage often stem from incorrect process parameters [4]. Since both warpage and shrinkage are affected by the combination of material properties and processing settings, minimizing shrinkage variation helps reduce warpage (Zhao et al., 2022; Shi et al., 2009). Other influential factors include the mechanical properties of the polymer, the cooling environment, and the angle of the runner's edge (Huszar et al., 2015). During the molding process, plastic starts as raw material, gets melted in a heated barrel, and is then injected into a mold cavity where it takes shape as it cools. In the automotive industry, manufacturers increasingly use thinner plastic components to reduce vehicle weight and improve fuel efficiency. This also reduces raw material consumption and cuts production time and costs [7].

By optimizing injection molding parameters, productivity can be significantly improved [8]. Simulation software helps identify potential faults early in the mold design process. For instance, Moldflow Plastic Insight (MPI) software can detect design flaws by simulating the filling and warping behaviors. A well-designed mold is critical to achieving high-quality parts with strong mechanical performance [9]. Key process settings include mold and melt temperatures, injection time, cooling duration, and packing pressure. Optimizing warpage before production begins is essential [10]. Additives such as pigments, talc, and glass can be mixed with plastics to alter their properties. Common defects like flow marks, sink marks, warpage, and burn marks can typically be corrected during the design stage. The position of the injection gate also significantly influences the way plastic fills the mold and solidifies. A well-placed gate shortens filling time and ensures even heat distribution across the mold cavity [11].

Original equipment manufacturers (OEMs) use mold flow analysis not just for defect prediction but also to remain competitive in the market. It helps in selecting materials and determining gate positions prior to tool production, and evaluates factors like fill time, temperature, and pressure to optimize the entire molding process. In this study, Moldflow Insight software was used to conduct simulation experiments. The optimal gate settings were identified through tool development, and warpage in the cladding component was observed using both an inspection fixture and actual vehicle fitment. Figure 1 outlines the molding process used in this research.

A detailed literature review shows that significant gaps still exist in the field of injection molding research and innovation. While artificial intelligence is gaining traction, its application remains limited. For example, Selvaraj et al. (2022) explored machine learning in molding applications, but few studies have managed to integrate multiple AI technologies into a single, adaptive system. The real-time adaptability of such systems remains underdeveloped, with most research focusing on individual use-cases rather than holistic, multivariable process control.

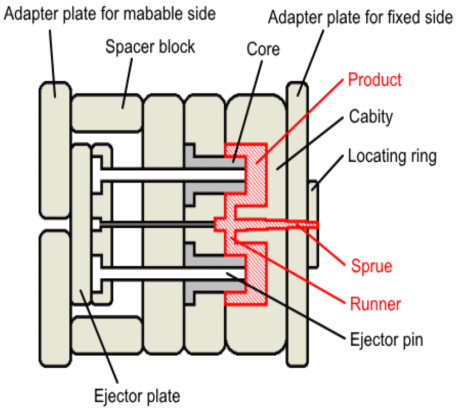

Figure 1. Outline of molding

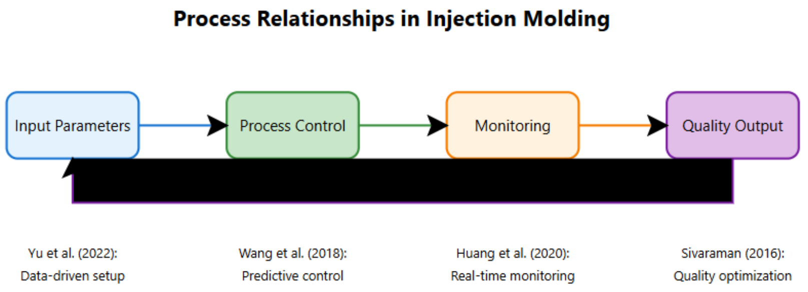

Figure 2. Process relationships in injection molding

In the realm of sustainable manufacturing, foundational work by Huszar et al. (2015) laid the groundwork for integrating energy efficiency and environmental concerns into production practices. However, considerable gaps remain—particularly in the application of life cycle assessments to injection molding processes. While the incorporation of biodegradable materials presents a promising avenue, current research falls short in addressing how to maintain part performance while using environmentally friendly alternatives. Moreover, studies often focus on isolated process improvements rather than examining energy efficiency across the entire production chain through a holistic lens.

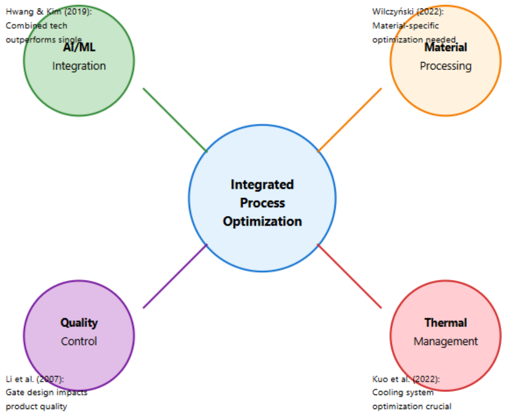

Figure 3. Integrated process optimization

Arman and Lazoglu's (2023) contributions to the development of conformal cooling channels represent progress, yet challenges persist in the implementation of adaptive cooling systems that can respond dynamically to real-time process changes. There is still a lack of comprehensive integration between cooling control mechanisms and broader process management systems. Similarly, while efforts like those by Huang, Ke, and Liu (2020) introduced cavity pressure-based adjustment techniques, the industry continues to lack dynamic optimization frameworks capable of adapting to material variability during production.

In terms of quality control, current systems are limited in their ability to predict defects and ensure real-time assurance during the molding process. This study addresses these limitations by focusing on optimizing gate numbers within the runner system of injection-molded components to reduce warpage. Using Mold Flow Analysis, the CAD model of the part is analyzed to observe deformation patterns under different gating setups.

Specifically, the study compares the effects of 6-drop and 8-drop runner systems on part geometry and identifies the configuration that results in lower shape distortion. By refining the gate design, the goal is to produce higher-quality parts with fewer defects. The research aims to establish a structured method for improving the gating system in injection molding, ultimately leading to enhanced part quality and faster, more efficient manufacturing processes.

2. Method

This study was carried out at an industrial facility specializing in the production of injection-molded parts for the automotive industry. The focus is on a Plastic Cladding Trim component, manufactured from Polypropylene (PP), which is an interior part mounted on car doors. This trim not only supports auxiliary components but also contributes to the vehicle's aesthetics, sound insulation, and thermal efficiency. A major challenge addressed in this research is determining the optimal number of gates in the injection molding process, while adhering to the stringent design criteria set by an Automotive OEM client. Any deviation from these specifications could negatively impact the part's functionality and long-term durability.

To address this, the study aims to enhance the component's design with respect to tooling practicality and performance. This is achieved through iterative simulations using Mold Flow Analysis (MFI) software. The software evaluates critical aspects such as material flow behavior, potential defect zones, and cooling system effectiveness. Based on these insights, an optimized gating system is developed to fulfill the client's performance and quality requirements, while also reducing manufacturing costs and lead times. The ultimate goal is to ensure the delivery of high-quality components that meet both technical specifications and customer expectations.

2.1 Process Flow Chart

The process flow diagram presented in Figure 4 was developed through collaborative brainstorming sessions involving a subject matter expert, a design engineer, and a quality manager from a renowned SUV manufacturing organization in India. This logical framework guided the sequential execution of the study. Based on the outlined flow, the analysis was carried out systematically, with results evaluated on both the revised CAD model and the physically manufactured component.

Figure 4 illustrates the process flowchart for optimizing the gating system of an injection-molded component. The objective is to minimize warpage and enhance production efficiency through systematic analysis and design refinement.

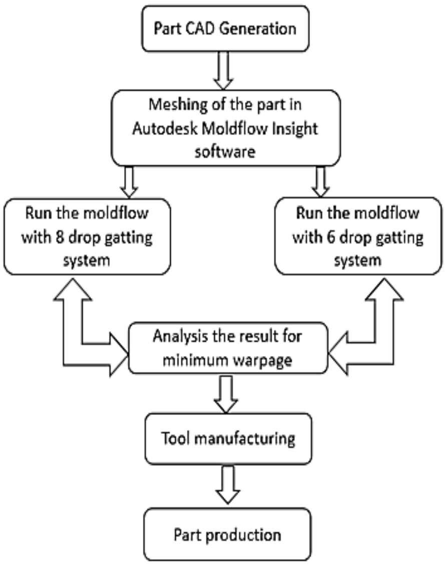

Figure 4. Process flow chart

2.2 Part CAD Generation

The plastic component is developed in accordance with the specified design requirements. Once finalized, the part is forwarded to the supplier for feasibility evaluation and subsequently sent for production tooling. Figure 5a and Figure 5b display the CAD representations of the part. In injection molding terminology, the A-surface refers to the exterior surface formed by the cavity side of the mold, typically visible in the final product, while the B-surface is the interior surface formed by the core side of the mold.


(a) (b)

Figure 5 (a, b). CAD image of the part

2.3 Six (6) and eight (8)-drop gating system

Figure 7 illustrates a 6-drop gating system used in injection molding for a plastic cladding component. The design features symmetrical runners (depicted in red) extending from a central sprue and branching out to six gates. Green cladding is applied around the runner system to provide thermal insulation and structural stability. This balanced runner configuration promotes uniform cavity filling and consistent flow distribution. The layout adheres to the design principles outlined by Jamsheed et al. (2015), particularly in terms of gate positioning and runner geometry. The inclusion of Y-junctions helps regulate flow resistance, while the cladding aids in maintaining thermal consistency during the molding process.

Figure 8 presents an 8-drop gating system with a similar cladded runner setup. In this design, a hierarchical branching structure extends from a central sprue to eight gates. The green cladding again serves as thermal insulation and mechanical support for the runner network. This configuration, based on the guidelines from Li et al. (2007), ensures balanced melt distribution by maintaining uniform flow paths and optimized runner cross-sections. The design is intended to achieve consistent pressure across all cavities, minimizing potential molding defects and promoting overall part quality.

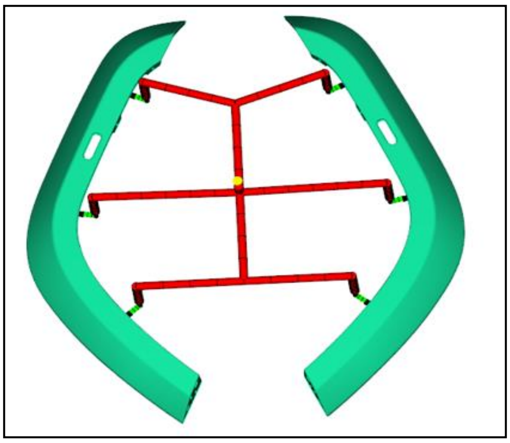

Figure 7. Six (6) drop gating system with cladding

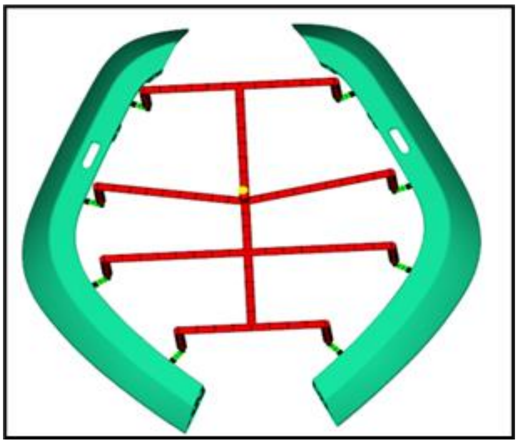

Figure 8. Eight (8) drop gating system with cladding

3. Result and Discussion

Fill Time Analysis plays a crucial role in identifying optimal process parameters by evaluating the time required to fill the mold cavity during injection molding. In this case, the complete cavity filling occurs within 4 seconds. Although reducing cycle time can enhance production efficiency, sufficient fill time is essential to maintain part quality. The analysis incorporates material characteristics and mold temperature settings to achieve an optimized filling process. Results obtained through mold flow simulation software allow for fine-tuning of processing conditions. Figures 9 and 10 present a comparative analysis of fill times for the 6-drop and 8-drop gating systems, highlighting the influence of gate design on fill time and overall molding efficiency.

3.1 Fill time study with 6-drop gate system

Figure 9 presents the fill time analysis for the mold cavity utilizing a 6-drop gating system. The color-coded contour map illustrates the progression of material flow, with blue representing the initial fill regions and yellow indicating the final areas to be filled. The simulation, conducted using Autodesk Moldflow Insight, shows that the cavity achieved complete filling in 3.819 seconds, with an average flow rate of 503.5970 cm³/s. Gates labeled Vg_01 to Vg_06 facilitated uniform distribution of the molten material, ensuring balanced cavity filling. This analysis confirms the efficiency of the 6-drop gate configuration in promoting consistent material flow throughout the mold.

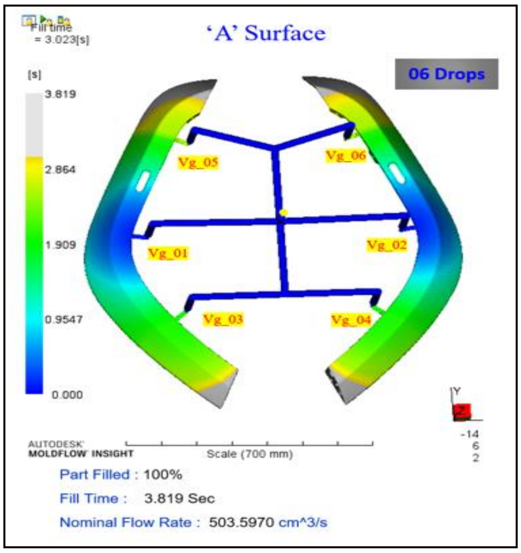

Figure 9. Fill time study with 6 drop gates

3.2 Fill time study with 8-drop gate system

Figure 10 displays the fill time analysis for the mold cavity using an 8-drop gating system, visualized through a color-coded contour map. The gradient ranges from blue, indicating regions filled first, to yellow, representing areas filled last. Although the cavity achieved 100% filling, the analysis revealed uneven material distribution. The total fill time was reduced to 3.648 seconds, with an average flow rate of 508.3537 cm³/s. The system utilized eight gates (Vg_01 to Vg_08), with Vg_07 and Vg_08 introduced to enhance filling efficiency. Autodesk Moldflow Insight results indicate that while the 8-drop configuration improves fill time, the observed imbalance in flow distribution suggests that further optimization is necessary to ensure consistent part quality.

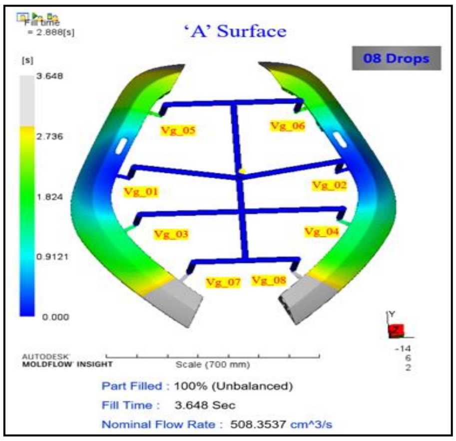

Figure 10. Fill time study with 8 drop gate

3.3 Warpage (Deflection) analysis with 6 drop gate system

. Figure 11 illustrates the deflection analysis of the plastic cladding component molded using a 6-drop gating system. The results are presented through a color gradient, with red indicating areas of higher deflection and blue representing regions with minimal deflection. The analysis, conducted using Autodesk Moldflow Insight, shows a maximum warpage of 7.738 mm in the positive direction. Although deflection is relatively uniform across the component, the results suggest that even minor deviations may impact the dimensional accuracy of the final product. Overall, the 6-drop gate system demonstrates effective warpage control, but further refinement may be needed to meet tight dimensional tolerances.

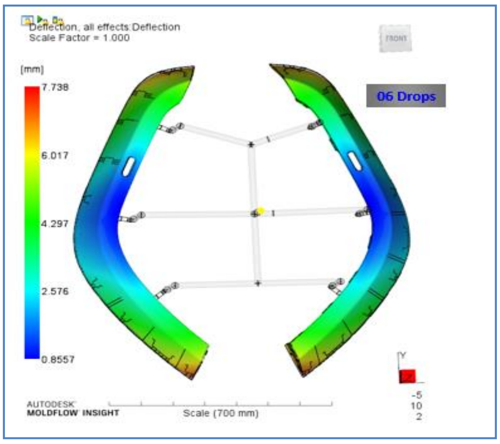

Figure 11. Deflection with 6 drop gate system

3.4 Warpage (Deflection) analysis with 8 drop gate system

Figure 12 presents the deflection analysis of the plastic cladding component using an 8-drop gating system. The results are visualized with a color gradient, where red indicates regions of high deflection and blue represents areas with minimal deformation. The analysis reveals a maximum deflection of 14.55 mm, with a consistent positive directional bias across the part. The deformation is accurately represented using a scale factor of 1.000.

Significant deflection is observed at the curved ends of the component, which serve as critical zones. The deflection pattern begins at the central area and extends outward, with more stable regions near the gates. Warpage values range from 0.8428 mm in areas adjacent to the gates to the maximum 14.55 mm at the part's outer edges, displaying a generally symmetrical distribution. Intermediate regions show deflection values between 4.295 mm and 11.20 mm.

This analysis was carried out using Autodesk Moldflow Insight, incorporating finite element analysis at a 1,000 mm scale, and leveraging rainbow spectrum visualization to clearly indicate deformation gradients. The high maximum deflection indicates potential manufacturing concerns, especially at the component's ends, where excessive warpage suggests insufficient support and cooling efficiency. The observed gradient also reflects inconsistencies in material flow and thermal distribution, and the extent of deformation likely exceeds standard dimensional tolerance limits.

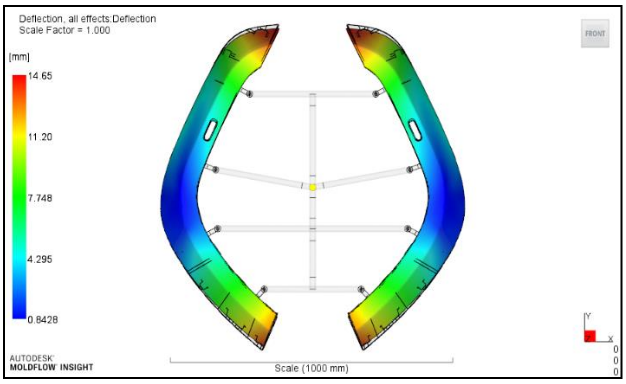

Figure 12. Deflection with 8 drop gate system

Experimental analysis using Moldflow Insight software confirmed that the 6-gate runner system delivered superior warpage performance compared to the 8-gate configuration, as illustrated in Figures 11 and 12. The 6-gate system demonstrated lower deflection values, all within acceptable quality thresholds, thus satisfying the dimensional accuracy requirements of the component. Following a comprehensive review involving the Supplier Quality In-Charge, Toolmaker Expert, and OEM representatives, the 6-gate runner system was selected for the tool kick-off phase. This decision reflects a well-balanced approach that prioritizes both performance consistency and manufacturing feasibility, ensuring minimized warpage and a reliable, efficient production process.

4. Conclusion

The study evaluated warpage behavior using Mold Flow Analysis applied to the initial CAD geometry, identifying warpage as a critical factor influencing overall part quality. A comparative analysis of the 6-drop and 8-drop runner systems revealed that the 6-drop configuration offered superior warpage control. As a result, the 6-drop gating system was selected as the optimal design, providing improved dimensional accuracy and reducing the likelihood of defects.

Mold Flow Analysis played a key role in identifying potential development and cooling issues at an early stage, enabling timely design modifications. This proactive optimization contributed to lower component costs and shorter lead times, thereby enhancing the product’s competitiveness in the market. The refined gating system not only improved part quality but also increased production efficiency, ultimately supporting greater market share and customer satisfaction.

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