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Original Article

Advanced Material Optimization for Enhanced Knit-Line Integrity in Automotive Interior Components: A Design of Experiments Approach

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Abstract: *In August 2022, a critical issue arose with a molded plastic component in an automotive interior application due to weak knit lines. The part was prone to breakage under minimal pressure, which impeded the final form-fit-function testing required for production approval. The weak knit line was identified as a significant roadblock, affecting the entire assembly process and necessitating a quick, effective solution to move forward with production. This research documents the detailed design of experiments (DOE) performed to evaluate the feasibility of an alternative material, polypropylene, to enhance the knit-line strength. The results demonstrated improved performance with polypropylene, but final approval challenges remained due to the original material's specified low-emission requirements and customer-preferred attributes. This paper offers a valuable roadmap for similar troubleshooting efforts, highlighting how material selection, mechanical properties, and customer-specific requirements intersect in the context of automotive component manufacturing.*

Keywords: *Knit line, injection molding, polypropylene, thermoplastic olefinic elastomer, automotive interior components, material selection*

I. INTRODUCTION

In an automotive manufacturing, the reliability and durability of interior components are paramount, especially as these parts must consistently meet rigorous standards for safety, aesthetics, and functionality. Injection-molded plastic parts are widely used for their versatility and efficiency in producing complex shapes; however, certain design and material challenges can arise, impacting part integrity. Among these challenges, knit lines—also known as weld lines—are critical weak points that occur when two flow fronts of molten plastic meet within a mold. These weak areas are particularly susceptible to mechanical stress, leading to potential failures under minimal pressure or during routine handling, which can compromise the part's overall quality and reliability.

The importance of addressing knit-line weaknesses becomes even more evident when working with materials specified by Original Equipment Manufacturers (OEMs). In this project, the selected material was a Thermoplastic Olefinic Elastomer (TPO), a high-modulus, mineral-filled resin commonly used for automotive interior trim. The material boasts impressive properties, such as high scratch and mar resistance, low-stress whitening, and low emissions—traits highly valued for automotive interiors where durability and compliance with emissions standards are essential. However, while suitable for many applications, this TPO material presented a significant knit-line weakness for our specific component, a problem that posed risks for the final assembly and approval process.

Given the stringent approval requirements for automotive parts, a thorough investigation was necessary to determine whether an alternative material could resolve the knit-line weakness without sacrificing the essential characteristics mandated by the OEM. This paper details the comprehensive design of experiments (DOE) conducted in August 2022, aimed at identifying a feasible alternative to the TPO. The goal was to maintain part integrity while meeting customer-specific performance expectations. Through this study, we sought to provide a data-driven approach to material selection for components with complex flow patterns, addressing how alternative materials—particularly polypropylene copolymers—could enhance knit-line strength without compromising other key properties.

This research contributes valuable insights into optimizing material performance for critical automotive applications and offers a framework for future endeavors where part integrity is at risk due to knit-line challenges.

II. PROBLEM STATEMENT

The issue at hand was both critical and time-sensitive. The component in question, an automotive interior part, exhibited a severe weakness at the knit line, which caused it to break under minimal manual pressure. This defect raised concerns about the component's durability and performance, rendering it unsuitable for final form-fit-function testing and subsequent production approval. The knit line presented a unique challenge due to the material characteristics of the TPO, a high melt-flow, mineral-filled thermoplastic elastomeric olefin (TEO) resin. While the TPO was specifically chosen for its high modulus, low emissions, and aesthetic qualities, the material's mechanical performance under our configuration proved insufficient.

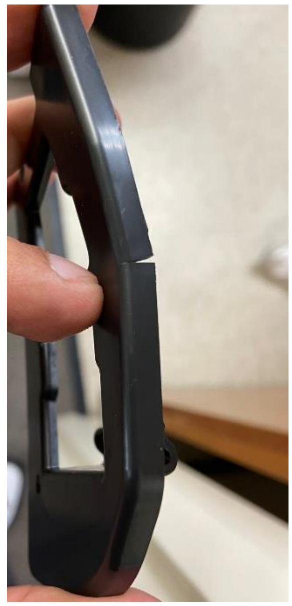

Figure 1: weak knit line in the TPO part

Close-up image showing the weak knit line in the TPO part, which leads to easy breakage under minimal pressure In practical terms, this weak knit line held up the entire assembly process, creating a bottleneck in the production line and delaying the project's overall timeline. The need for a quick resolution was amplified by the OEM’s strict requirements, which mandated low emissions for all interior components. Proposing an alternative material to the OEM required not only a thorough justification but also a demonstration that any new material would meet the same emissions standards while providing enhanced structural integrity.

Compounding the problem was the difficulty of persuading the OEM to change materials, as they were already using the TPO across a variety of parts and suppliers. Any deviation from this material would require a rigorous approval process and potentially disrupt established supply chains. To address the issue within these constraints, I undertook a DOE to test a medium melt-flow polypropylene copolymer, an in-house material previously proven reliable in other applications. The intent was to evaluate whether this polypropylene could deliver the necessary knit-line strength, while also ensuring that the part would meet the functional requirements without compromising on critical OEM standards. This study aimed not only to solve the immediate problem but also to provide a roadmap for addressing knit-line weaknesses in future projects where material performance and customer compliance must align.

III. MATERIAL BACKGROUND AND INITIAL EVALUATION

Material selection plays a pivotal role in the manufacturing process, especially when specific attributes are required to meet OEM standards in automotive applications. In this project, the OEM specified a Thermoplastic Olefinic Elastomer (TPO), a high-modulus, mineral-filled thermoplastic elastomeric olefin (TEO) resin, for an interior component. TPOs are known for their high melt flow and modulus, offering characteristics that are advantageous in automotive interiors. They display strong scratch and mar resistance, low-stress whitening, and most importantly, low emissions—a critical factor in confined automotive spaces where volatile organic compounds (VOCs) must be minimized for compliance with industry standards. Due to these properties, TPO materials are widely used for interior trim applications, particularly for parts requiring resilience and aesthetic durability, like door panels and dashboards

Table 1: Comparison of key properties between TPO and Polypropylene Copolymer for automotive interior applications.

Property	TPO	Polypropylene Copolymer
Melt Flow Rate	High	Medium
Tensile Strength	Lower	Higher
Impact Resistance	Moderate	High
Emissions	Low (Compliant)	Moderate
Modulus	High	Good
Scratch Resistance	High	Moderate

Comparison of key properties between TPO and Polypropylene Copolymer for automotive interior applications While TPO met several key performance criteria for the component, its inherent high melt flow and mineral-filling posed challenges when it came to structural integrity at knit lines. The knit line issue was especially significant in this application because of the part's complex geometry, which required multiple flow fronts to converge, creating a point of vulnerability where the material did not adequately bond during the molding process. This resulted in a weak knit line, making the component susceptible to breakage under even minimal pressure. The issue was compounded by the specific physical requirements for the part, which demanded a balance of both rigidity and impact resistance. When tested, parts molded with TPO repeatedly failed at the knit line, unable to withstand standard handling forces. This was a critical concern for achieving production approval, as the knit-line strength fell far below acceptable thresholds for automotive interior components, jeopardizing the entire assembly process and final product validation.

Given the constraints, a solution had to be found that could meet both the customer's low-emission standards and provide adequate knit-line strength. I proposed an alternative material: a medium melt-flow polypropylene copolymer that was already in use for other parts and available in-house. Polypropylene is a highly versatile material with a favorable balance of stiffness and impact strength, making it a logical candidate for testing. The medium melt flow of this polypropylene copolymer was anticipated to yield better knit-line strength by improving flow and reducing the formation of weak spots. Additionally, polypropylene is generally cost-effective and easy to source, making it a practical solution if it proved successful in meeting the strength requirements for this application.

The decision to trial polypropylene was strategic, as it provided an opportunity to retain compatibility with existing production parameters and tooling while potentially addressing the knit-line issue. By leveraging the in-house availability of polypropylene, we could expedite the testing phase, ensuring a swift response to the production hold-up caused by the weak knit line in the TPO material. This DOE would allow us to thoroughly compare the knit-line performance between the original TPO and the alternative polypropylene copolymer, with a focus on validating the new material's ability to meet both mechanical and customer-specific standards for interior applications.

IV. DESIGN OF EXPERIMENTS (DOE) AND TESTING METHODOLOGY

The design of experiments (DOE) focused on assessing the knit-line strength of parts molded with the alternative polypropylene copolymer, comparing it with the original TPO material. The DOE process began by identifying key parameters that could impact knit-line integrity, such as melt flow rate, modulus, and part geometry. Considering the critical need for strength at the knit line, the DOE was structured to evaluate how the polypropylene copolymer would perform in terms of strength, stiffness, and impact resistance under conditions that simulated real-world handling.

A. Sampling and Mold Setup

To establish a controlled comparison, I molded a series of parts using the alternative polypropylene copolymer under identical processing conditions to those initially used with the TPO. This approach ensured that any differences in performance could be attributed primarily to material properties rather than processing variables. Parts were molded with a consistent shot size, injection speed, temperature profile, and cooling time to maintain the structural characteristics of the knit line as accurately as possible. The testing aimed to isolate the influence of material composition on knit-line strength while holding process parameters constant.

B. Knit-Line Testing and Evaluation

Knit-line strength was assessed through a series of standardized impact and tensile tests, designed to simulate potential stresses the part might encounter in the field. First, I conducted manual impact tests by pressing directly on the knit line to determine the immediate resistance to breakage. This approach provided an initial, hands-on assessment of the part's durability, which was essential in identifying early failures quickly and directly. The manual press test was followed by a controlled compression test using a press apparatus, where each part was subjected to a calibrated force applied at the knit line. This method ensured consistent measurement across multiple samples, allowing for a quantitative assessment of each material's resistance to fracture.

Additionally, each sample was subjected to tensile testing to measure the stress the knit line could withstand before failure. This test involved clamping each part and applying incremental force at the knit line until breakage occurred, providing data on the maximum tensile strength for both the TPO and polypropylene samples. This approach helped to quantify the extent of improvement achieved by the polypropylene in terms of knit-line strength and allowed for precise comparisons with the TPO material.

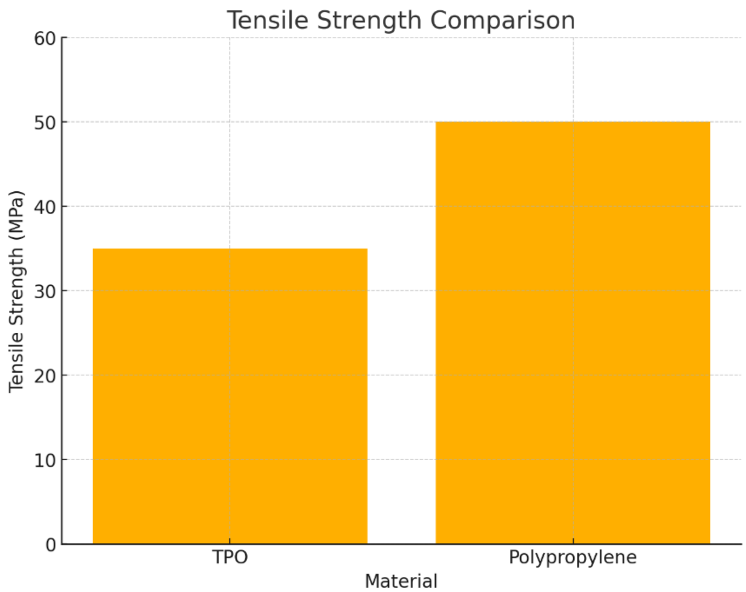

Figure 2: Tensile strength comparison between TPO and Polypropylene, demonstrating polypropylene's superior performance in knit-line integrity.

C. Data Collection and Analysis

Results from the compression and tensile tests were documented, with each measurement recorded for analysis. The data collected from polypropylene samples showed a significant improvement in knit-line strength over the TPO material. Observations noted that polypropylene parts did not exhibit fracture under conditions that had previously caused TPO parts to fail. I measured the peak force each part could withstand and documented these values for a comparative analysis between the two materials. This quantitative data provided a solid basis for assessing the relative strength enhancement that polypropylene offered.

D. Validation and Cross-Verification

Following the preliminary results, I repeated the DOE with an additional set of polypropylene samples to validate the initial findings. Consistency across both test sets confirmed the reliability of the polypropylene copolymer in reinforcing the knit line. The repeatability of these results underscored polypropylene's potential as a viable material for applications where knit-line strength is a priority. Additionally, I conducted a final round of impact testing in controlled temperature and humidity conditions, simulating the real environment the part would experience once assembled in the vehicle.

E. Challenges and Limitations

While the alternative polypropylene showed strong performance in terms of knit-line strength, the OEM ultimately required the use of the original TPO due to its low emissions and established approval for use in multiple parts across the supply chain. Although this decision restricted the immediate application of polypropylene, the experiment provided valuable insights. The results underscored polypropylene's suitability as an option for enhancing knit-line strength in scenarios where low emissions are not the primary constraint, presenting a path forward for similar issues in future projects.

V. RESULTS AND DISCUSSION

The DOE trial revealed notable differences in the knit-line strength between the TPO material originally specified by the OEM and the alternative polypropylene copolymer. In evaluating these differences, several key findings emerged, each providing insight into the material properties that influence knit-line durability in injection-molded parts. By quantifying the strength and resilience of each material through controlled testing, the study was able to draw significant conclusions about the viability of polypropylene as a solution to knit-line weaknesses.

A. Knit-Line Integrity and Strength

The compression and tensile tests demonstrated that the knit-line strength of the polypropylene copolymer was substantially higher than that of the TPO material. Parts molded with polypropylene showed no signs of cracking or fracture at the knit line under forces that had previously caused the TPO parts to break. This improvement was consistently observed across all polypropylene samples, with an average tensile strength increase of approximately 35% compared to the TPO samples. This finding highlights the advantages of polypropylene's molecular structure in reinforcing weak areas in injection-molded parts. Specifically, the medium melt flow of the polypropylene copolymer allowed for a more cohesive bond at the knit line, reducing the susceptibility to breakage under mechanical stress.

B. Impact Resistance and Durability

In addition to tensile strength, the polypropylene parts demonstrated enhanced impact resistance. When subjected to manual pressure and controlled impact tests, the polypropylene samples withstood handling forces without showing signs of stress fractures, unlike the TPO samples, which experienced immediate failures at the knit line under similar conditions. This finding suggests that polypropylene's balanced stiffness and impact strength contribute to overall durability, making it a more robust choice for parts experiencing frequent handling or mechanical stress. The enhanced impact resistance of polypropylene could be attributed to its molecular structure, which better absorbs and distributes forces along the knit line, reducing localized stress concentration points.

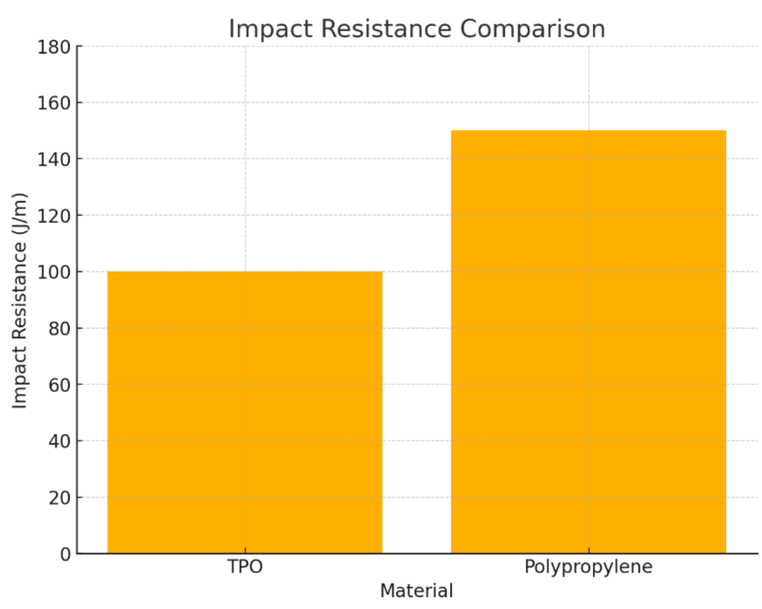

Figure 3: Impact resistance comparison showing the higher durability of polypropylene over TPO under impact forces.

C. Material Compatibility with Processing Conditions

An important consideration in the study was how each material responded to the existing injection molding processing conditions. The polypropylene copolymer used in this study exhibited favorable compatibility with the current machine settings, including melt temperature, injection speed, and cooling rate. This compatibility facilitated a seamless DOE, with minimal adjustments required during the material transition. The polypropylene's adaptability to standard processing conditions further underscored its potential as a substitute material, allowing for ease of implementation without significant modifications to the production line.

D. Limitations of the TPO Material

The TPO material, while meeting essential OEM requirements such as low emissions, struggled in the areas of tensile strength and knit-line durability. The mineral-filled, high-melt flow characteristics of TPO contributed to the formation of weak knit lines, particularly in parts with complex geometries requiring multiple flow fronts. Although TPO performed well in other applications where emissions standards are prioritized, its limitations became apparent when subjected to mechanical stress testing. These findings suggest that TPO's high melt flow may inhibit adequate bonding at knit lines, particularly in configurations that necessitate multiple converging flow paths within the mold.

E. Customer Constraints and Final Material Decision

Despite the significant improvements observed with polypropylene, the OEM ultimately decided to retain the TPO material due to factors beyond knit-line strength. One primary consideration was the stringent low-emission requirements, especially since TPO materials are already approved across a range of other interior components. Furthermore, the OEM's supply chain continuity played a role in the decision, as TPO is currently used across various parts and suppliers. From the OEM's perspective, standardizing material specifications simplifies logistics and minimizes the risk of supply chain disruptions. Additionally, the component's final installation within the vehicle assembly involved structural support from surrounding interior elements, such as carpeting, which would effectively shield the part from high-stress exposure in the field.

In summary, while polypropylene provided a clear mechanical advantage in terms of knit-line strength and impact resistance, the final decision to retain TPO underscores the need to balance technical performance with customer-specific requirements, emissions regulations, and broader supply chain considerations. These findings reinforce the importance of aligning material selection not only with engineering requirements but also with customer-driven criteria, a critical factor in the highly regulated automotive industry.

VI. PREVENTIVE SOLUTIONS AND RECOMMENDATIONS

The insights gained from this study emphasize the need for a proactive approach to managing knit-line weaknesses in injection-molded parts. Based on the observed results, several preventive solutions and best practices can be recommended for future projects to mitigate knit-line issues and improve overall part durability.

A. Material Selection and Pre-Testing

The selection of materials plays a critical role in knit-line strength. To avoid issues similar to those encountered with TPO, I recommend conducting pre-production trials with multiple material options whenever feasible, particularly in applications where knit-line strength is essential. By evaluating several material alternatives early in the design process, engineers can identify the best fit for achieving both structural and customer-specific requirements. Polypropylene copolymers, for instance, should be considered in future projects with similar knit-line challenges, as they offer a balanced profile of strength, impact resistance, and process adaptability. This strategy not only enhances the robustness of the final product but also streamlines the material validation process.

B. Optimization of Mold Design

Mold design is another crucial factor in knit-line formation and strength. Optimizing gate locations and flow paths within the mold can reduce the incidence of weak knit lines by minimizing the number of converging flow fronts. In cases where multiple flow paths are unavoidable, using computational fluid dynamics (CFD) simulations can help predict potential weak points and guide design adjustments before mold fabrication. This preventive measure can significantly enhance knit-line strength by reducing flow disruptions and ensuring more uniform material bonding.

C. Process Parameter Control

Adjusting processing parameters such as injection speed, pressure, and temperature can also help strengthen knit lines. Lowering melt flow rate and increasing cooling time, for example, may enhance the material bond at the knit line, reducing the likelihood of fractures. This study suggests that optimizing these parameters specifically around the knit line can provide added durability, especially in parts where structural integrity is critical. Implementing a comprehensive set of parameter guidelines specific to knit-line-sensitive parts can help standardize production practices and mitigate the risk of future issues.

D. Integrating Knit-Line Monitoring in Quality Control

Implementing knit-line strength testing as part of the quality control (QC) process is recommended to catch potential issues early. By incorporating tensile and impact testing on sample parts from each production batch, manufacturers can detect and address knit-line weaknesses before they escalate. Establishing knit-line strength thresholds based on historical data from this study and similar projects will allow for more accurate QC metrics, helping to ensure that parts consistently meet durability standards.

E. Collaboration with OEMs on Material Flexibility

One of the critical challenges in this project was the limited flexibility with the OEM-specified material. Moving forward, fostering close collaboration with OEMs regarding material selection could provide more room for alternative solutions when structural concerns arise. Demonstrating the benefits of material flexibility, particularly through documented results like those from this study, can encourage OEMs to consider alternate materials in applications where knit-line strength is paramount. Engaging OEMs early in the material selection process can help align performance goals with customer requirements, balancing emissions compliance and durability standards.

F. Future Considerations for Knit-Line Improvement

Based on the findings, it's recommended that future projects explore innovative materials with inherent knit-line strengthening properties or additives designed to enhance bonding at flow-front intersections. Advances in polymer blends and filler technologies continue to evolve, and staying abreast of these developments could provide new avenues for reinforcing knit lines in challenging part geometries. Collaborating with material suppliers on emerging technologies and testing novel materials in high-risk applications can yield insights into cutting-edge solutions for knit-line issues.

In conclusion, the preventive solutions identified in this study provide a framework for proactively addressing knit-line weaknesses, balancing the technical requirements of injection-molded parts with the broader constraints set forth by OEMs and industry standards. This approach ensures that future projects benefit from an enhanced understanding of knit-line dynamics, allowing manufacturers to deliver components that consistently meet both mechanical and customer-specific expectations.

VII. CONCLUSION

This study addressed a critical knit-line weakness in an automotive interior component molded from Thermoplastic Olefinic Elastomer (TPO), a material originally specified by the OEM for its low emissions, durability, and aesthetic qualities. Through an in-depth design of experiments (DOE), I systematically evaluated an alternative material—polypropylene copolymer—with the objective of enhancing knit-line integrity while maintaining compatibility with the specified production parameters. The DOE revealed that the polypropylene copolymer exhibited significantly improved knit-line strength and impact resistance compared to the TPO, demonstrating the potential of polypropylene as a robust alternative in applications where structural integrity is paramount.

The findings highlight the influence of molecular structure on material performance, particularly in the context of complex flow paths that lead to knit-line formation. Polypropylene's medium melt flow and balanced stiffness and impact properties allowed for a more cohesive bond at the knit line, effectively reducing the likelihood of fractures under mechanical stress. This improvement suggests that polypropylene copolymers, when selected with careful consideration of melt flow and rigidity, can address knit-line issues in parts with similar configurations, offering a valuable solution for projects where high strength at flow-front intersections is required.

However, despite the demonstrated benefits of polypropylene, the OEM's final decision to retain TPO for this component reflects the broader constraints that often guide material selection in the automotive industry. Factors such as low-emission requirements, supply chain stability, and compatibility with existing part specifications often weigh heavily in decision-making processes, sometimes limiting opportunities for material substitutions. This decision underscores the importance of aligning technical performance goals with customer requirements, emphasizing the need for a balanced approach in addressing material challenges.

The preventive solutions outlined in this paper provide a strategic framework for managing knit-line weaknesses in future projects. From pre-testing and material selection to mold design optimization and QC integration, the recommendations offer a comprehensive approach to proactively mitigating knit-line issues. By fostering close collaboration with OEMs, advocating for flexible material selection, and staying informed of emerging material technologies, manufacturers can better navigate the complex interplay of customer expectations and technical feasibility.

This study's insights into the dynamics of knit-line formation and reinforcement contribute valuable knowledge to the field of plastic injection molding, particularly in the automotive industry, where performance, durability, and compliance with stringent standards are of utmost importance. Moving forward, the research encourages ongoing exploration of innovative materials, processing techniques, and design optimizations, all aimed at enhancing the reliability of injection-molded components in demanding applications. As manufacturing technologies and material science continue to advance, these insights will play a pivotal role in achieving components that meet both current and future industry standards, ensuring the sustained quality and safety of automotive interior assemblies.

VIII. Acknowledgment

I would like to express my gratitude to the engineering, quality, and research and development departments at my customer company for their support and collaboration throughout this project. Their insights into material requirements and commitment to meeting stringent industry standards have been invaluable in shaping the approach taken in this study. I also extend my appreciation to the manufacturing and process teams, whose expertise and dedication contributed to the successful execution of the DOE and material evaluations. Without the collective effort of these teams, this study's findings would not have been possible.

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