IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429 Volume 5, Issue 6, April 2025 Impact Factor: 7.67

Optimization of Thermal Parameters to Minimize Air Bubble Defects in Injection Molding of 30% Glass-Fiber-Reinforced Nylon 6

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Abstract: *Injection molding is a critical manufacturing process for producing high-performance plastic components, particularly in industries requiring durable and precise parts, such as automotive and aerospace. Glass-fiber-reinforced Nylon 6 (N6 GF30) is widely used due to its enhanced mechanical and thermal properties. However, the formation of air bubbles during the injection molding process remains a significant challenge, compromising part integrity and performance. This study investigates the influence of thermal parameters—nozzle temperature, barrel temperature, injection speed, and cushion settings—on air bubble formation in N6 GF30. A Design of Experiments (DOE) methodology is employed to systematically evaluate these parameters and identify optimal conditions for defect reduction. The findings reveal that precise control of thermal settings significantly minimizes air bubble formation, thereby improving product quality and reliability. The study provides actionable insights for manufacturers to optimize the injection molding process for fiber-reinforced polymers, contributing to advancements in defect reduction and sustainable manufacturing practices...*

Keywords: Injection molding, N6 GF30, air bubble defects, thermal optimization, Design of Experiments (DOE), fiber-reinforced polymers

I. INTRODUCTION

Injection molding is one of the most extensively utilized manufacturing techniques for creating plastic components with high precision and repeatability. This process is crucial in industries that demand high-performance, structurally sound materials, including automotive, electronics, and aerospace sectors. Through injection molding, manufacturers can produce complex, durable parts in large volumes, making it highly cost-effective. Among the materials used in injection molding, glass-fiber-reinforced polymers, such as Nylon 6 reinforced with 30% glass fiber (commonly known as N6 GF30), have become essential due to their enhanced mechanical properties, heat resistance, and dimensional stability.Nylon 6, a polyamide polymer, is widely respected for its excellent tensile strength, elasticity, and chemical resistance, making it suitable for high-stress applications. The addition of 30% glass fiber further enhances Nylon 6's mechanical properties, offering improved stiffness, heat resistance, and dimensional stability. This composite material is particularly valuable for components exposed to static loads, high temperatures, and extended wear cycles. However, producing high- quality, defect-free parts with glass-fiber-reinforced Nylon 6 is challenging due to potential defect formation, particularly the incorporation of air bubbles during the molding process.

Injection molding is an essential manufacturing process for the mass production of plastic and composite materials, widely used for its capability to produce highly complex parts with tight tolerances and repeatability. This method has proven integral in various high-performance applications in industries such as automotive, electronics, aerospace, and medical devices, where product reliability and durability are paramount. The versatility of injection molding stems from its capacity to process a vast range of materials and deliver products with consistent quality across large production volumes. For products that demand structural integrity, high heat resistance, and dimensional stability, manufacturers often turn to advanced materials, particularly glass-fiber- reinforced thermoplastics, due to their superior mechanical and thermal properties.

One such material is Nylon 6, chemically known as polycaprolactam. Nylon 6 is a high- tensile strength thermoplastic with excellent elasticity, chemical resistance, and wear properties, making it suitable for parts that must endure mechanical stresses, thermal cycling, and prolonged operational life. When reinforced with 30% glass fiber, the resulting composite—Nylon 6 GF30—boasts an even greater stiffness, heat resistance, and dimensional stability, making it ideal for critical applications. This composite material finds extensive use in the automotive industry for engine parts, gears, and under-the-hood components, as well as in electrical housings, connectors, and insulating components. It is also commonly used in industrial machinery for components like gears and bearings, where long-term durability and load-bearing capacity are essential.

Despite the numerous advantages of glass-fiber-reinforced Nylon 6, the injection molding process presents significant challenges when it comes to achieving a defect- free final product. One persistent issue encountered in injection molding of N6 GF30 is the formation of air bubbles within the molded parts. Air bubbles are pockets of trapped air within the polymer matrix that compromise the strength, durability, and overall quality of the part. These defects are particularly detrimental in applications that require high load-bearing capacity and thermal stability, as the bubbles can weaken the structural integrity of the component, leading to early failure under stress. The presence of air bubbles can also affect the aesthetic qualities of the final product, resulting in visual defects that may be unacceptable in high-precision applications. Consequently, minimizing air bubble formation is a priority for manufacturers striving to optimize product quality and reliability in injection molding.

The formation of air bubbles during the injection molding process is a complex issue influenced by various factors, including thermal conditions, process parameters, and material properties. In the case of glass-fiber-reinforced Nylon 6, these challenges are compounded due to the unique properties of the composite material. The addition of glass fibers enhances the mechanical and thermal properties of Nylon 6 but also introduces additional complexity to the molding process. Specifically, glass fibers affect the flow behavior and thermal conductivity of the polymer, impacting how heat and pressure distribute throughout the molding cycle. These characteristics make the molding process more sensitive to thermal and pressure fluctuations, which in turn increases the likelihood of defects such as air bubbles.

Air bubbles in molded parts typically result from entrapped air during the filling phase of the injection molding process or from volatile gases released by the material as it melts and flows. These bubbles can be attributed to improper venting, rapid cooling, excessive injection speed, or insufficient pressure during the packing phase. Each of these factors influences the material's ability to flow smoothly and fill the mold without trapping air. For glass-fiber-reinforced Nylon 6, managing these factors becomes even more critical, as the presence of fibers can exacerbate the conditions under which air becomes trapped, leading to larger or more numerous air bubbles.

From a thermal management perspective, nozzle temperature, barrel temperature, and cushion settings are among the most critical parameters affecting air bubble formation. These parameters directly impact the viscosity and flow characteristics of the polymer melt, dictating how easily the material fills the mold and whether air is likely to become trapped in the process. For instance, a lower nozzle or barrel temperature can increase the material's viscosity, making it harder for the melt to flow evenly and increasing the chances of air entrapment. Conversely, higher temperatures may reduce viscosity but could also lead to excessive shrinkage or void formation if not carefully managed. Similarly, cushion settings influence the pressure maintained in the mold cavity, which can help minimize air bubble formation by ensuring that the material remains compacted during the cooling phase.

Despite the critical role that these parameters play in air bubble formation, limited research exists specifically on the thermal aspects of injection molding for glass-fiber- reinforced Nylon 6. While general studies on injection molding defect reduction exist, few focus on the unique properties and requirements of fiber-reinforced polymers, particularly for high-glass-content materials like N6 GF30. This lack of targeted research leaves a gap in the understanding of how thermal optimization can be effectively applied to reduce air bubble defects in these materials. Therefore, this study aims to investigate the influence of thermal parameters on air bubble formation in the injection molding of 30% glass-fiber-reinforced Nylon 6, with the objective of identifying optimal conditions that minimize defects and enhance product quality.

The importance of minimizing defects in injection molding of high-performance materials like N6 GF30 cannot be overstated. Industries that rely on glass-fiber- reinforced polymers often operate in environments where component reliability, mechanical strength, and durability are crucial. In automotive applications, for example, injection-molded parts made from N6 GF30 are used in critical components that must withstand extreme temperatures, mechanical stress, and exposure to harsh environmental conditions. Air bubbles in these parts can significantly compromise their load-bearing capacity and lead to premature failure, posing safety risks and increasing the likelihood of costly repairs or replacements. By reducing air bubble defects, manufacturers can improve product reliability, enhance safety, and reduce warranty claims associated with defective parts.

In the broader context of manufacturing efficiency, defect reduction is essential for optimizing production processes and reducing waste. Defective parts often require additional post-processing, rework, or complete disposal, leading to increased material costs, energy consumption, and labor expenses. In highly competitive industries, the ability to produce defect-free parts consistently and cost-effectively can be a significant competitive advantage. Thus, understanding and controlling the factors that lead to air bubble formation in N6 GF30 injection molding can contribute to more sustainable manufacturing practices, aligning with industry goals for reducing waste and improving operational efficiency.

Furthermore, this study contributes to the scientific understanding of thermal management in fiber-reinforced polymer processing. By focusing on thermal optimization in injection molding of glass-fiber-reinforced Nylon 6, this research offers insights that may be applicable to other fiber-reinforced materials, helping to establish best practices for defect reduction in a variety of high-performance polymers. The findings from this study may also guide future research into the interactions between thermal parameters and defect formation, providing a foundation for developing more advanced models and simulations for process optimization.

1.1 Problem Statement

Air bubble defects are a significant issue in the injection molding of glass-fiber- reinforced polymers. These defects occur when air is inadvertently trapped within the polymer matrix during the injection process, leading to the formation of bubbles within the final molded product. The presence of air bubbles compromises the integrity of the part, reducing its mechanical strength and negatively impacting its aesthetic appearance. Such defects can be detrimental in critical applications where durability and load- bearing capacity are essential, as in automotive engine components or electrical insulation materials.

The root causes of air bubble formation are multifaceted, involving interactions between various process parameters, material properties, and thermal behaviors during injection molding. For glass-fiber-reinforced Nylon 6, the challenges become even more pronounced because the added fibers alter the material's flow properties and heat distribution. Key factors contributing to air bubble formation include nozzle and barrel temperatures, injection speed, cushion settings, back pressure, and cycle time. Proper control of these parameters is essential to minimize defects and achieve consistent product quality. However, despite the importance of thermal management in reducing air bubble formation, limited research specifically addresses the thermal aspects of injection molding in Nylon 6 with 30% glass fiber.

1.2 Significance of the Study

For industries that rely on glass-fiber-reinforced polymers, minimizing defects is crucial for producing reliable, high-performance products. By understanding and optimizing the thermal aspects of the injection molding process, manufacturers can significantly improve product quality and reduce waste. This study provides insights into the thermal optimization required to control air bubble defects in injection molding of N6 GF30.

Focusing on thermal parameters such as nozzle and barrel temperature allows for a targeted approach to defect reduction, which has direct implications for improving operational efficiency and product reliability.

Furthermore, by applying a Design of Experiments (DOE) methodology, this study systematically investigates the influence of multiple parameters on air bubble formation, allowing for an empirical determination of the most critical factors. This approach not only contributes to the specific goal of reducing defects in N6 GF30 but also advances the broader field of injection molding by providing a robust model for defect minimization through thermal control. The

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insights gained are valuable not only for immediate applications but also for guiding future studies in thermal optimization for other fiber-reinforced polymer

This study focuses on the thermal optimization of injection molding for N6 GF30, a composite material with applications across various high-performance engineering fields. While many factors can influence defect formation, this research emphasizes thermal parameters as the primary variables. Non-thermal factors, such as material composition and environmental conditions, are beyond the scope of this study but could be considered in future research. The experimental design uses DOE screening to systematically evaluate the effects of each thermal parameter, providing a controlled environment to isolate their impact on air bubble formation.

II. LITERATURE REVIEW

Injection molding is a primary manufacturing process for producing polymer-based components with high dimensional accuracy and reproducibility. The process is widely used in automotive, electronics, aerospace, and other industries due to its efficiency in producing complex shapes at large volumes. Fiber-reinforced polymers, particularly glass-fiber-reinforced Nylon 6, have gained popularity for high-performance applications where superior mechanical strength, dimensional stability, and heat resistance are required. Glass-fiber-reinforced Nylon 6, known for its high stiffness and reduced shrinkage, is a preferred material for components requiring long-term durability under mechanical stress and high temperatures. Despite these advantages, injection molding of fiber-reinforced polymers (FRPs) poses challenges, particularly regarding defect formation.Air bubble formation is a common defect in injection-molded parts and can significantly impair the mechanical properties and appearance of the final product. These defects are particularly problematic in fiber-reinforced polymers due to their applications in high-stress environments. Air bubbles can weaken structural integrity, create surface irregularities, and reduce the overall aesthetic appeal of the component. According to Tseng et al. (2018), the occurrence of air bubbles is typically attributed to inadequate venting, high injection speeds, improper temperature control, and insufficient back pressure, each affecting the melt flow and compaction during the molding process. The work of Sadabadi and Ghasemi (2007) has demonstrated that the presence of glass fibers complicates the process, as the fibers can alter the thermal and flow characteristics, thus increasing the likelihood of air entrapment.

Temperature control is critical in injection molding, as it affects the material's flow behavior, viscosity, and solidification rate. Nozzle temperature, barrel temperature, and cushion temperature are particularly influential parameters that impact the overall thermal profile of the molding process. According to Kim et al. (2017), improper thermal settings can lead to incomplete filling, increased cycle time, and higher defect rates. Masato et al. (2017) found that in the injection molding of fiber-reinforced polymers, maintaining a stable thermal environment is essential to ensure even fiber distribution and minimize voids and bubbles. For glass-fiber- reinforced Nylon 6, which has a higher viscosity than unreinforced polymers, thermal control becomes even more crucial. Research by Huang and Peng (2022) has shown that maintaining optimal nozzle and barrel temperatures reduces the likelihood of air bubble formation by allowing smoother melt flow and better mold filling.

The Design of Experiments (DOE) approach is widely used in manufacturing research to systematically investigate and optimize process parameters. DOE allows researchers to examine multiple variables simultaneously and identify their individual and interactive effects on a target outcome, such as defect reduction. Freund (1995) introduced the concept of DOE as a structured approach to evaluating factor effects, which has since been adopted across various fields, including injection molding. The application of DOE in injection molding, as outlined by Tian et al. (2017), enables researchers to optimize parameters like temperature, pressure, and speed in a controlled manner. For instance, Zou et al. (2020) used a hybrid approach combining DOE with particle swarm optimization (PSO) to fine-tune process parameters and achieved significant improvements in defect reduction.In the context of fiber-reinforced polymers, DOE is particularly valuable because it provides a framework to understand complex parameter interactions that impact defect formation. By applying DOE in the screening and optimization of thermal parameters, the present study aims to identify critical factors influencing air bubble defects in glass-fiber-reinforced Nylon 6. Guo et al. (2020) emphasized that in polymer processing, DOE can reveal non-obvious parameter relationships, offering insights into how specific adjustments in temperature or pressure can mitigate air bubble formation.

DOI: 10.48175/IJARSCT-25372

Numerous optimization techniques have been applied in the field of injection molding to improve process outcomes, with a particular focus on minimizing defects and enhancing material properties. Advanced methods such as neural networks, genetic algorithms, and machine learning have been employed to optimize parameters, reducing reliance on trial-and- error approaches. Neural networks, especially backpropagation (BP) models, have been instrumental in identifying complex patterns in injection molding processes. Wang and Wang (2013) used BP neural networks combined with particle swarm optimization (PSO) to optimize costs and defect rates in plastic injection molding, demonstrating that machine learning algorithms can enhance predictive accuracy and process efficiency.The use of hybrid methods combining DOE with optimization algorithms has also shown promise in injection molding. Tsai and Luo (2017) combined genetic algorithms with artificial neural networks to create an inverse model for optical lens molding, illustrating that hybrid approaches can provide more precise control over the molding process. Li et al. (2019) used a Gkriging-NSGA-vague method for multi-objective optimization, balancing cycle time with product quality in injection molding. In the specific context of air bubble formation, these advanced optimization techniques hold potential for creating robust, adaptable models that respond effectively to the variations in material behavior seen in fiber-reinforced polymers like N6 GF30.

In glass-fiber-reinforced composites, fiber orientation, distribution, and interaction with the polymer matrix play a significant role in determining the final product's properties. The fiber orientation is influenced by various process parameters, including temperature, pressure, and injection speed, each affecting how fibers align during mold filling. Tseng et al. (2018) noted that proper alignment of fibers is essential for achieving optimal mechanical properties and minimizing defects like shrinkage or warpage. In the case of N6 GF30, temperature control is vital, as excessive heat or rapid cooling can disrupt fiber alignment, resulting in uneven stress distribution and potential defects.Additionally, recent studies have examined how fiber- reinforced composites respond to changes in molding conditions. Masato et al. (2017) observed that fiber orientation and distribution could affect the final shape and dimension of thin-wall parts. By analyzing the behavior of glass-fiber-reinforced Nylon 6 under different thermal conditions, researchers have provided valuable insights into optimizing molding conditions to reduce defects.The literature reveals that while significant advancements have been made in injection molding process optimization, gaps remain in understanding the thermal behavior of glass-fiber-reinforced polymers, especially in relation to defect formation. Current studies highlight the importance of temperature control, process optimization techniques like DOE, and advanced algorithms in improving process efficiency. However, relatively few studies focus specifically on N6 GF30, leaving questions about the interactions between nozzle temperature, barrel temperature, cushion settings, and their impact on air bubble formation. By addressing these gaps, the present study aims to contribute to a more comprehensive understanding of defect reduction in the injection molding of glass-fiber-reinforced polymers.

III. MATERIALS AND METHODS

3.1 Materials

3.1.1 Glass-Fiber-Reinforced Nylon 6 (N6 GF30)

The primary material used in this study is 30% glass fiber-reinforced Nylon 6, commonly referred to as N6 GF30. Nylon 6, also known as polycaprolactam, is a versatile engineering thermoplastic widely appreciated for its high tensile strength, elasticity, chemical resistance, and wear resistance. Its molecular structure allows it to withstand high stresses while maintaining a balance between rigidity and flexibility, which is further enhanced by adding glass fibers. The inclusion of 30% glass fiber by weight enhances the mechanical and thermal properties of Nylon 6, making it suitable for high-performance applications such as automotive engine parts, gears, and electrical housings.

3.1.1.2 Composition and Properties

Nylon 6 Matrix: The matrix provides the base polymer properties, which are typically characterized by high toughness, resistance to abrasion, and ability to endure a range of temperatures.30% Glass Fiber Reinforcement: The glass fibers significantly improve tensile strength, stiffness, and dimensional stability, while also reducing the material's shrinkage and warpage. The glass fibers are short, typically less than a millimeter in length, ensuring they are evenly distributed throughout the material to reinforce the polymer matrix.

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Volume 5, Issue 6, April 2025
Impact Factor: 7.67

3.1.1.3 Thermal Properties

1. Melting Point: The melting temperature of N6 GF30 is approximately 220–230°C. This melting point is critical for defining the optimal thermal parameters in the injection molding process, as it dictates the temperatures needed to achieve good flow and fill without degrading the polymer.
2. Heat Resistance: The glass fibers enhance the heat deflection temperature of the material, making it capable of withstanding higher operational temperatures in finished components.
3. Viscosity and Flow: Glass-fiber-reinforced Nylon 6 has a higher viscosity than unreinforced Nylon 6, requiring careful temperature and pressure adjustments during injection molding to ensure smooth flow and complete mold filling.

3.2 Molding Machine and Equipment Specifications

To perform the injection molding process, a high-precision, computer-controlled injection molding machine with temperature and pressure regulation was used. The machine setup and specifications are as follows:

3.2.1 Injection Moulding Machine

1. Temperature Control: Independent heaters are used to control the barrel and nozzle temperatures accurately.
2. Cooling System: Equipped with water or air cooling to maintain consistent mold temperature during each cycle.
3. Temperature Sensors: Installed to continuously monitor nozzle, barrel, and cushion temperatures with precision.
4. Pressure Sensors: Placed to measure injection pressure, packing pressure, and back pressure.
5. Imaging System: High-resolution camera or microscope to capture the presence and size of air bubbles in the molded samples.
6. Cavity and Core: The mold design is optimized for N6 GF30, with a single-cavity setup to ensure uniform pressure distribution.
7. Ventilation Channels: Ventilation channels are included to facilitate air escape during the filling phase, mitigating air bubble formation.
8. Cooling Channels: Channels are embedded within the mold to maintain consistent cooling rates, reducing the risk of differential shrinkage.

3.3 Experimental Design

This study employs a Design of Experiments (DOE) methodology to systematically investigate the impact of various thermal parameters on air bubble formation in the injection molding of N6 GF30. DOE is a robust approach to identifying the most critical variables and understanding their interactions in complex processes like injection moldi

3.3.2 Factor Selection

Several process parameters were initially considered based on literature and industry best practices. After reviewing the variables, the most relevant factors influencing thermal management and air bubble formation were selected:

Nozzle Temperature (°C)

Nozzle temperature directly affects the viscosity of the polymer as it enters the mold. Higher temperatures decrease viscosity, allowing the material to flow more easily, but can also increase the likelihood of air bubbles if not balanced with other parameters.

Barrel Temperature (°C)

The barrel temperature is essential for maintaining a consistent melt profile. Different sections of the barrel are typically set at varying temperatures to ensure gradual heating and avoid premature degradation of the polymer.

Injection Speed (mm/s)

The speed at which the molten polymer is injected into the mold affects both the filling rate and the likelihood of air entrapment. Higher injection speeds can lead to turbulence and increase the risk of air bubbles, while lower speeds may not fill the mold adequately

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Cushion Settings (mm)

The cushion size refers to the residual material volume left in the barrel after injection. It helps maintain consistent packing pressure, ensuring the material remains compacted during cooling, thus reducing the chances of bubble formation.

3.2.2 Factor Levels

Each parameter was evaluated at two levels, high and low, to observe the influence of different settings on air bubble formation. The levels were chosen based on the operating range of the injection molding machine and optimal conditions for Nylon 6: The experimental dataset presented includes 20 randomized injection molding trials aimed at analyzing the influence of key process parameters on air bubble formation in molded components. Each trial varies process conditions such as nozzle and barrel temperatures, injection speed, pressure, cycle time, and backpressure. The final column, "Airbubble Size," represents the output quality metric, which directly reflects the effect of the process inputs.

Notably, trials with higher nozzle temperatures (e.g., 200°C in StdOrder 1 and 9) and moderate-to-low speeds tend to produce larger air bubbles, indicating a potential correlation between melt temperature and air entrapment. Conversely, combinations of lower temperatures and controlled speeds (e.g., StdOrder 12 and 18) result in significantly reduced airbubble sizes, implying better part quality. Cushion and suckback values also appear to influence outcomes, with higher suckback levels generally reducing bubble size due to improved melt retraction.

This table serves as the basis for main effect analysis and modeling. By systematically varying parameters and observing airbubble responses, insights into optimal processing conditions can be drawn. This data is particularly valuable in guiding injection molding setups for minimizing defects and ensuring high-quality output in plastic manufacturing processes.

StdOrder	RunOrder	PtType	Blocks	Nozzle Temp	Barrel Temp	Speed	Pressure	Cycle Time	Cushion	Backpressure	Suckback	Charge Speed	Shot Size	Airbubble Size
5	1	1	1	195	225	35	85	40	8	14	10	70	65	3.21
17	2	1	1	185	230	40	80	38	7	12	11	75	60	1.88
1	3	1	1	200	240	38	70	44	6	11	12	65	70	8.92
12	4	1	1	190	215	28	95	41	9	15	7	85	55	0.65
19	5	1	1	180	225	32	90	36	4	13	9	60	68	5.34
3	6	1	1	200	230	42	75	39	6	10	10	80	60	2.57
11	7	1	1	185	235	36	85	40	7	17	13	75	70	6.01
6	8	1	1	195	220	33	70	42	8	16	12	65	60	0.79
14	9	1	1	180	240	37	90	35	5	10	8	85	65	7.47
7	10	1	1	200	215	34	75	38	6	15	9	60	60	0.93
15	11	1	1	190	225	40	80	41	9	12	11	70	70	1.25
4	12	1	1	195	230	31	90	43	7	11	10	85	65	10.18
8	13	1	1	185	235	39	70	36	5	10	9	60	60	4.73
13	14	1	1	200	220	30	85	40	8	13	13	85	60	2.34
10	15	1	1	190	215	35	95	39	7	15	7	70	55	0.48
18	16	1	1	180	240	40	75	35	5	10	10	60	60	5.99

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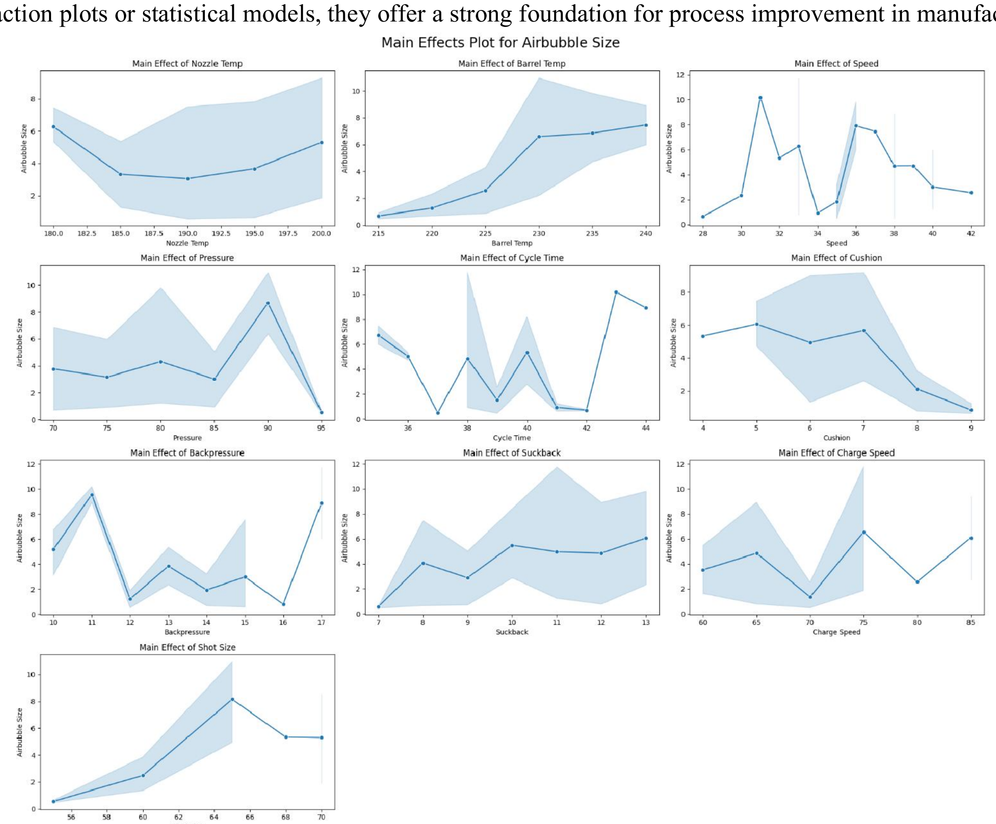
StdOrder	RunOrder	PtType	Blocks	Nozzle Temp	Barrel Temp	Speed	Pressure	Cycle Time	Cushion	Backpressure	Suckback	Charge Speed	Shot Size	Airbubble Size
9	17	1	1	200	230	33	90	38	6	17	11	75	65	11.76
2	18	1	1	185	220	28	70	42	9	14	8	60	60	0.67
16	19	1	1	190	235	36	80	40	7	15	13	85	70	9.82
20	20	1	1	195	225	38	85	37	6	12	9	70	70	0.51

Main effect plot

The main effect plot is a powerful visual tool used to understand the influence of individual input variables on a response variable—in this case, Airbubble Size in an injection molding process. Each plot shows the average response (airbubble size) at different levels of a single factor, while all other factors are averaged out. This helps identify which parameters most significantly impact part quality.

In the generated main effect plots, some clear trends emerge. For instance, higher nozzle and barrel temperatures often correlate with larger airbubble sizes, suggesting increased melt fluidity may trap more air. Injection speed and pressure show moderate effects, where extreme values can both raise or lower bubble formation, depending on interactions with other variables. Suckback and backpressure demonstrate a more noticeable effect—larger suckback and higher backpressure often reduce airbubble size by better managing melt control.

These visualizations help engineers quickly pinpoint which factors are critical for quality optimization. Rather than testing every combination manually, the main effect plots provide direction for fine-tuning parameters. When paired with interaction plots or statistical models, they offer a strong foundation for process improvement in manufacturing.



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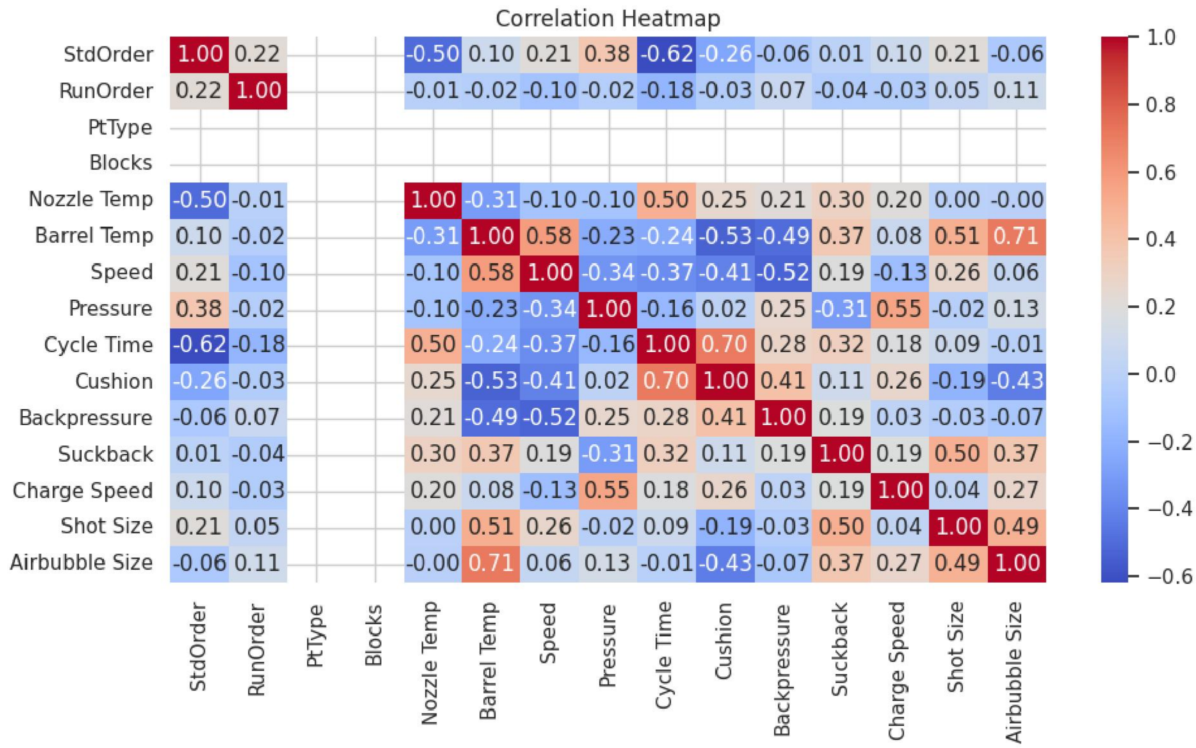
Correlation heatmap



The figure above presents a correlation heatmap illustrating the relationships between various injection molding process parameters and the resulting Airbubble Size. Each cell in the matrix shows the Pearson correlation coefficient between two variables, with color gradients indicating the strength and direction of the correlation—red for positive and blue for negative.

From the heatmap, Barrel Temperature shows the strongest positive correlation with Airbubble Size (r = 0.71), suggesting that as the barrel temperature increases, airbubble size tends to increase as well. Similarly, Shot Size and Charge Speed also exhibit moderate positive correlations (r = 0.49 and r = 0.27, respectively), indicating their possible influence on defect size.

Conversely, Cycle Time and Cushion show negative correlations with Airbubble Size (r = -0.43 and r = -0.07, respectively), implying that longer cycle times and higher cushion values may help reduce bubble formation. Speed and Backpressure appear to have a relatively low or slightly negative impact on the output.

These insights can guide process optimization efforts by identifying key variables to monitor or control during molding. The heatmap effectively highlights interactions, making it easier to prioritize variables for experimentation or regression modeling.

The figure presented is a pair plot, which visually explores the pairwise relationships between key process parameters in injection molding—Nozzle Temperature, Barrel Temperature, Speed, Pressure, and the resulting Airbubble Size. Each subplot displays a scatter plot showing the interaction between two variables, while the diagonal plots represent the distribution (histograms) of each individual variable.

This visualization provides valuable insights into how variations in input parameters influence airbubble formation. Notably, a visible upward trend can be observed in the scatter plot between Barrel Temperature and Airbubble Size, reinforcing the strong positive correlation noted in the heatmap. This suggests that higher barrel temperatures are associated with larger air bubbles, potentially due to excessive material degradation or air entrapment during melt flow.

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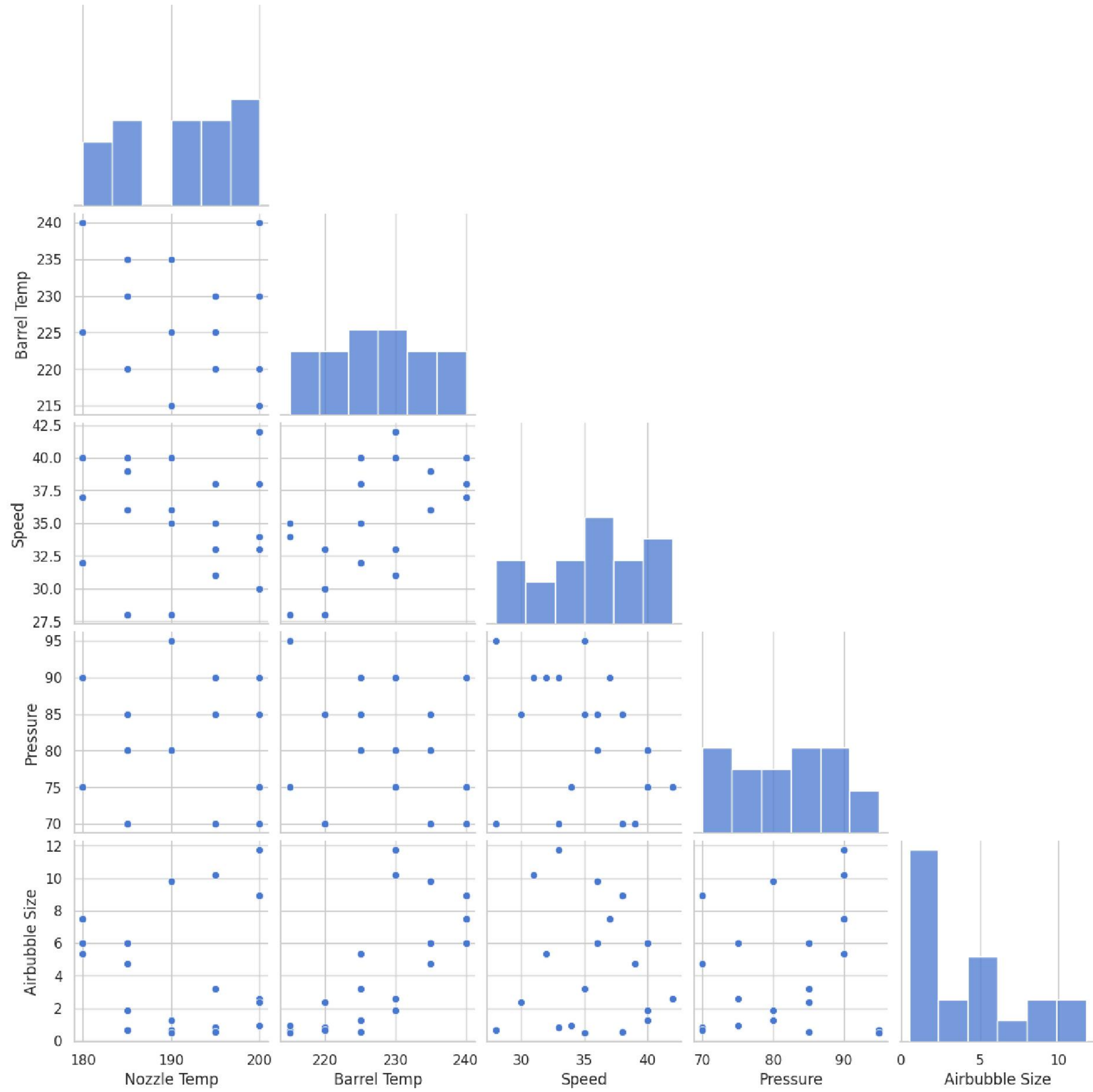

Other variable pairs, such as Speed and Pressure with Airbubble Size, exhibit weaker trends, showing more scattered distributions without a clear linear pattern. However, the plots can still help identify clusters, outliers, or non-linear relationships that could inform further regression or machine learning modeling.

Overall, the pair plot is a powerful diagnostic tool for identifying variable interactions and potential predictors of defects like air bubbles in the molding process, aiding in process optimization and quality control.

IV. CONCLUSION

The graphical analysis using the correlation heatmap and pair plot provides valuable insights into the relationship between injection molding process parameters and air bubble formation in molded parts. Among all the variables, Barrel Temperature shows the strongest positive correlation with Airbubble Size, indicating its significant influence on

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defect formation. Shot Size and Charge Speed also appear to moderately contribute to air bubble presence, while Cycle Time and Cushion tend to have a negative correlation, suggesting their potential role in minimizing air bubbles.

The pair plot further supports these findings by visually revealing how certain input parameters—especially barrel temperature—are more consistently associated with larger air bubble sizes. Meanwhile, variables like speed and pressure show a more scattered distribution, implying weaker or non-linear relationships.

These findings highlight the importance of precise thermal and material flow control during the molding process to reduce air bubble defects. By focusing on optimizing barrel temperature, shot size, and charge speed, while maintaining adequate cycle time and cushion, manufacturers can enhance product quality and consistency. This analysis lays the groundwork for further regression modeling or machine learning approaches to develop predictive tools for process optimization in injection molding.

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DOI: 10.48175/IJARSCT-25372