

## Simulation-Based Optimization of Plastic Transfer Molding Parameter for IC Package Encapsulation Process

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### ABSTRACT

*This study focuses on the simulation-based optimization of plastic transfer molding parameters in the Quad Flat No-Lead (QFN) encapsulation process, which is widely used in the semiconductor industry due to its compact size and reliable performance. However, process-related issues such as air traps, incomplete filling, and uneven curing can compromise product quality, leading to performance failures and higher rejection rates. To address these challenges, this study aims to analyze and optimize critical molding parameters to minimize such defects and improve the consistency of the QFN package. Four key numerical parameters, such as mold temperature, melt temperature, curing time, and injection pressure, were selected based on their significant influence on flow behaviour and material curing. The study employs Response Surface Methodology (RSM) with a Central Composite Design (CCD) to systematically evaluate the effect of each parameter and its interactions. A total of 30 simulation runs were generated using Design Expert software, and Autodesk Moldflow was used to simulate the transfer molding process. The results demonstrated that optimized settings significantly reduced defects, with validation showing minimal percentage differences (<10%) in key responses, including 0.0000% for Fill time, 0.0000% for Air traps, 0.0607% for Curing level, 1.7179% for Shear rate, and 0.1246% for Shear stress. This study concludes that simulation-based optimization effectively improves the QFN encapsulation process, ensuring better quality and process consistency. Future research could focus on experimental validation, integration of advanced materials, and real-time monitoring to further enhance the process.*

**Keywords:** Central Composite Design (CCD), Design Expert, Plastic Transfer Molding, Quad Flat No-Lead (QFN), Response Surface Methodology (RSM).

### 1. INTRODUCTION

The rapid advancement of microelectronics has driven increasing demand for compact, high-performance, and cost-effective packaging technologies. Among the various surface-mount packages, the Quad Flat No-Lead (QFN) package, as shown in Figure 1, has gained widespread adoption due to its small footprint, excellent electrical performance, and superior thermal dissipation. These attributes make QFN packaging especially suitable for high-density consumer electronics, automotive systems, and wireless communication devices [1].

A critical step in the QFN assembly process is plastic transfer molding, where a thermosetting molding compound is injected into a mold cavity under pressure to encapsulate the semiconductor die. This process is essential for ensuring mechanical protection, environmental sealing, and structural integrity of the package [2]. However, the process is inherently sensitive to several parameters, such as mold temperature, transfer pressure, and curing time, which directly affect the quality of encapsulation. Improper control of these parameters can lead to

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defects such as voids, delamination, wire sweep, and incomplete cavity filling, all of which can significantly degrade the device's electrical and thermal reliability [3].

Traditionally, parameter tuning in the molding process relies on operator experience or on iterative trial-and-error methods. While such approaches may yield acceptable results, they are time-consuming, resource-intensive, and lack precision. Moreover, they often overlook parameter interactions, which can lead to inconsistent outcomes and quality variation. As the industry moves toward greater process automation and higher yield expectations, there is a clear need for systematic, data-driven methods to understand and optimize process parameters [4].

Simulation-based optimization offers a promising solution to these challenges. By integrating process simulation tools with statistical techniques such as Response Surface Methodology (RSM), it becomes possible to model the complex relationships between process variables and product quality. This approach enables engineers to predict and minimize defects, optimize process conditions, and improve overall manufacturing efficiency [5]. Within this context, the present study aims to apply RSM to analyze and optimize key parameters in the plastic transfer molding process for QFN encapsulation, thereby contributing to improved process control and package reliability.

The plastic transfer molding process is a vital step in the packaging of Quad Flat No-Lead (QFN) semiconductor components, where a molding compound encapsulates the chip to provide structural support and protection. However, the process is highly sensitive to parameters such as mold temperature, transfer pressure, and curing time. If these parameters are not carefully controlled, defects like voids, delamination, wire sweep, and incomplete filling can occur, compromising the reliability and performance of the final product.

In industrial settings, process optimization is often performed using trial-and-error methods or based on operator experience. These approaches are inefficient, costly, and fail to adequately capture the complex relationships among process parameters. Furthermore, the interaction effects between variables are frequently overlooked, even though they can significantly impact defect formation. A systematic, data-driven method is therefore required to identify significant factors and optimize parameter settings to ensure high-quality QFN encapsulation.

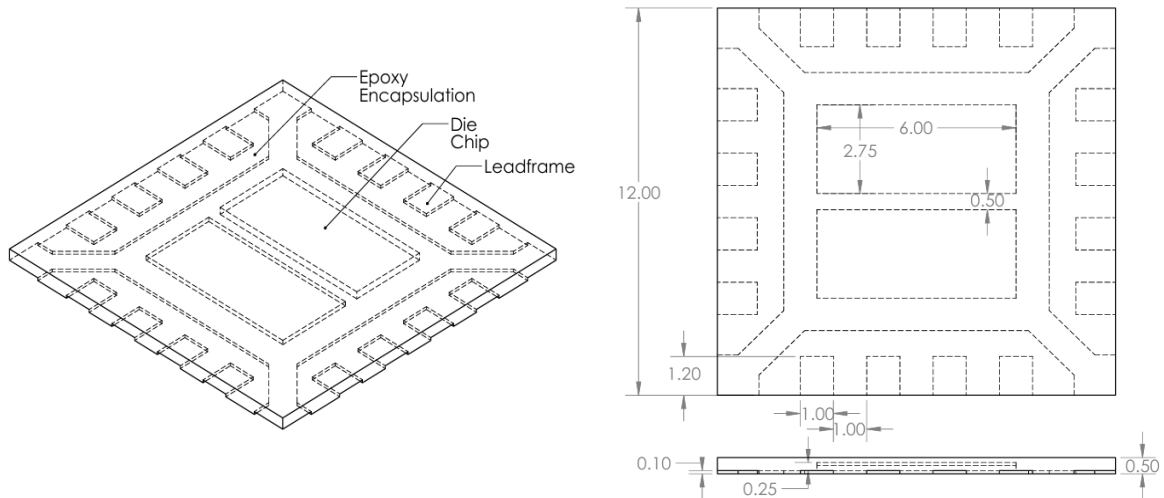
## **2. MATERIAL AND METHODS**

This research uses simulation-based methods to optimize the plastic transfer molding process for Quad Flat No-Lead (QFN) encapsulation. First, a 3D model of the QFN is created using SolidWorks and imported into Autodesk Moldflow Insight for simulation. The model is then meshed, and a grid sensitivity test ensures the mesh is of high quality. Key process parameters like mold temperature, melt temperature, curing time, and injection pressure are varied using the Design of Experiments (DOE) approach to study their effect on filling time, curing level, shear rate, shear stress, and air trap formation. The results are analyzed with statistical and graphical tools, such as regression models and ANOVA. The process is optimized based on these results, and the resulting settings are validated within an acceptable error margin of < 10%. If needed, further refinements are made to ensure the process meets the precision requirements for QFN encapsulation.

### **2.1 3D and Simulation Model Development**

The first step in the methodology is to create a 3D model of the QFN encapsulation layout in SolidWorks, as shown in Figure 1. The model is imported into Autodesk Moldflow Insight for simulation. A meshing process is used to discretize the geometry into smaller elements for analysis, as shown in Figure 2. The mesh quality is assessed, and a grid sensitivity test is

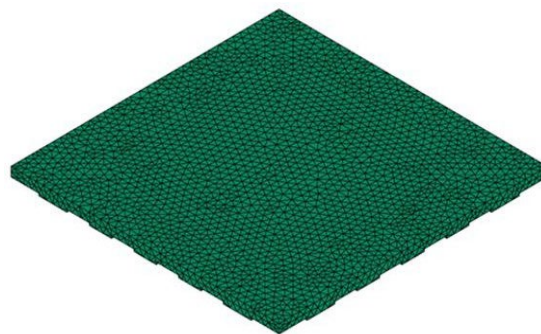
performed to ensure reliable simulation results. A global edge length of 0.32 mm is used, ensuring an optimal balance between accuracy and computational efficiency, as in Table 1.



**Figure 1:** 3D model of the QFN encapsulation and dimensions (mm).

**Table 1:** Mesh Statistics of Dual Domain.

Global Edge Length	0.32 mm
Aspect Ratio Maximum	6.53
Aspect Ratio Average	1.63
Aspect Ratio Minimum	1.16
Entity Counts:	
• Triangle	9142
• Connected Nodes	4573
• Connectivity Regions	1
Area: Surface Area	3.26596 cm <sup>2</sup>
Volume By Element Types:	
• Triangle	0.0559 cm <sup>3</sup>
Edge Details:	
• Free Edges	0
• Manifold Edges	13713
• Non-Manifold Edges	0
Match Percentage:	
• Match Percentage	96.2%
• Reciprocal Percentage	97.1%



**Figure 2:** Meshing of QFN Encapsulation.

### 2.1.1 Grid Sensitivity Test

To ensure the reliability and stability of the selected mesh size, a Grid Sensitivity Test was performed. This test involved running simulations with varying edge lengths and comparing the resulting aspect ratios. The percentage difference in aspect ratio between different mesh sizes was calculated to determine whether mesh size affects the results. To ensure the reliability and stability of the selected mesh size, a Grid Sensitivity Test was performed. This test involved running simulations with varying edge lengths and comparing the resulting aspect ratios.

A small percentage difference indicates that the mesh size does not significantly affect the results, suggesting that the chosen mesh size is stable and reliable. Table 2 shows the sensitivity results, which indicate minimal variation across cases, confirming that the selected mesh size provides consistent outcomes. Based on these findings, it was concluded that further refinement of the mesh size was unnecessary, as the percentage differences were minimal.

**Table 2:** Grid Sensitivity Test.

Case	Global edges length, mm	Aspect ratio, mm	Percentage difference, %
1	0.32	1.63	-
2	0.33	1.65	1.23
3	0.34	1.65	0
4	0.35	1.66	1.61
5	0.36	1.66	0

## 2.2 Material Selection

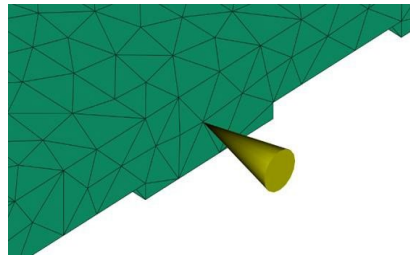
The material used for the encapsulation process is Epoxy Molding Compound (EMC), filled with 88% alumina ( $Al_2O_3$ ) for enhanced thermal and mechanical properties. EMC was chosen due to its low shrinkage, high dimensional stability, dielectric strength, and thermal resistance, making it ideal for semiconductor packaging. The alumina filler improves heat dissipation and the mechanical strength of the encapsulant. The material specifications are presented in Table 3.

**Table 3:** Material specifications.

Fibre/Filler	88% Alumina Filled
Melt Temperature	154
Melt Temperature Range	144-164
Mold Temperature Surface Range	165-185

### 2.2.1 Injection Location Selection

In this simulation, the injection location was carefully positioned at the side of the lead frame surface, as shown in Figure 3. This location was selected to ensure uniform flow distribution across the cavity and to minimize the risk of common molding defects such as air traps and incomplete filling. The injection point was defined in Autodesk Moldflow, and the mesh was generated to accommodate optimal material flow from this location throughout the transfer molding process.



**Figure 3:** Injection Location.

### 2.3 Determination of Quality Characteristics

In this study, five key responses were selected to evaluate the performance of the transfer molding process, such as filling time, air trap, curing level, shear rate, and shear stress. These outputs were chosen because they directly reflect the quality of the encapsulation and the effectiveness of the selected parameters. Filling time helps indicate how efficiently the resin fills the mold cavity. Air traps identified in the V/P analysis log indicate the presence of voids that can lead to structural weaknesses. Meanwhile, curing level (measured by bulk conversion) represents how completely the material has hardened, which is essential for ensuring the mechanical strength and thermal stability of the final product.

In addition, shear rate and shear stress were included to understand how the resin behaves as it flows through the cavity. Excessive shear may cause material degradation or internal stress, while low shear might result in incomplete flow. By monitoring these five responses throughout the simulations, the process can be fine-tuned to minimize common defects and ensure optimal encapsulation quality. These responses also serve as a guide for determining the most balanced combination of process parameters during the optimization phase.

### 2.4 Selection of Influential Factors and Responses

In this project, a structured, simulation-based optimization approach was implemented to evaluate the influence of selected numerical process parameters on the plastic transfer molding process for Quad Flat No-Lead (QFN) encapsulation, as shown in Table 4. The encapsulation material used was Epoxy Molding Compound (EMC) filled with 88% alumina, chosen for its excellent thermal stability, low shrinkage, and strong mechanical properties, making it highly suitable for semiconductor packaging. The entire simulation workflow was carried out using Autodesk Moldflow Insight, enabling detailed analysis of material flow, curing behaviour, and defect formation during the molding process.

Four numerical parameters were selected for analysis: mold temperature, melt temperature, curing time, and injection pressure. These factors were identified based on their significant impact on encapsulation quality, such as flow consistency, curing completeness, and part durability. A Response Surface Methodology (RSM) using Central Composite Design (CCD) was applied to efficiently explore both main and interaction effects of these variables [6]. The simulation experiments were designed to identify optimal conditions with minimal trial-and-error systematically.

Key simulation outputs included filling time, air trap formation, curing level, shear rate, and shear stress. Air traps were used as indicators of void formation that could weaken mechanical strength, while curing level was monitored through bulk conversion analysis to ensure proper hardening of the material [6]. Shear rate and shear stress were essential for assessing flow dynamics and internal material resistance, both of which are important in preventing defects such as warping or delamination [7]. By analyzing these outputs, the process was successfully optimized to improve product quality and reduce defect rates in QFN encapsulation.

**Table 4:** Levels of Processing Parameters.

Factor	Level		
	1	2	3
Mold temp, °C	165	175	185
Melt temp, °C	144	154	164
Curing time, s	24	30	36
Injection pressure, MPa	144	180	216
Material	EMC + 88% Alumina		

## 2.5 Analysis and Optimization

The simulation data is analyzed using statistical tools, including regression models and Analysis of Variance (ANOVA). The key responses were evaluated through perturbation plots, interaction graphs, and 3D surface plots. The optimization of the parameters was performed using Design-Expert software, with the goal to minimizing defects in filling time, air traps, shear rate, and shear stress, while maximizing the curing level. The final optimized process parameters were validated by comparing predicted results with actual simulation outcomes, with an acceptable error margin of <10%.

**Table 5:** Levels of Processing Parameters.

Run	Factors				Responses				
	A	B	C	D	X1	X2	X3	X4	X5
	°C	°C	s	MPa	s	%	%	1/s	MPa
1	185	164	36	144	4.999	0.96	0.6568	1746.1	0.2407
2	175	154	36	180	4.998	0.99	0.4390	1746.2	0.3153
3	175	154	30	180	4.998	0.99	0.3530	1746.2	0.3153
4	165	164	36	144	4.999	0.97	0.2402	1746.1	0.2829
5	175	154	30	180	4.998	0.99	0.3530	1746.2	0.3153
6	165	164	36	216	4.999	0.97	0.2402	1746.2	0.2829
7	165	164	24	216	4.999	0.97	0.1304	1746.2	0.2829
8	175	154	30	180	4.998	0.99	0.3530	1746.2	0.3153
9	165	144	24	144	4.999	0.96	0.1285	1746.1	0.4181
10	165	144	24	216	4.998	0.96	0.1284	1746.2	0.4181
11	175	144	30	180	4.998	0.93	0.3530	1746.1	0.3676
12	185	164	24	216	4.998	0.96	0.4631	1746.2	0.2407
13	175	154	24	180	4.998	0.99	0.2632	1746.2	0.3153
14	165	144	36	144	4.999	0.96	0.2379	1746.1	0.4181
15	185	144	36	216	4.999	0.97	0.6564	1746.2	0.3284
16	165	164	24	144	4.999	0.97	0.1304	1746.1	0.2829
17	185	154	30	180	4.998	0.96	0.5707	1746.2	0.2797
18	175	164	30	180	4.998	0.99	0.3544	1746.2	0.2636
19	185	164	36	216	4.998	0.96	0.6584	1746.2	0.2407
20	165	154	30	180	4.999	0.96	0.1816	1746.1	0.3474
21	185	164	24	144	4.999	0.96	0.4631	1746.1	0.2407
22	175	154	30	216	4.998	0.99	0.3530	1746.2	0.3153
23	175	154	30	180	4.998	0.99	0.3530	1746.2	0.3153
24	185	144	36	144	4.999	0.97	0.6564	1746.1	0.3284
25	185	144	24	144	4.999	0.97	0.4625	1746.1	0.3284
26	185	144	24	216	4.999	0.97	0.4625	1746.2	0.3284
27	165	144	36	216	4.998	0.96	0.2379	1746.2	0.4181
28	175	154	30	144	4.998	0.99	0.3530	1746.1	0.3153
29	175	154	30	180	4.998	0.99	0.3530	1746.2	0.3153
30	175	154	30	180	4.998	0.99	0.3530	1746.2	0.3153

A: Mold Temperature; B: Melt Temperature; C: Curing Time; D: Injection Pressure  
X1: Filling Time; X2: Air Trap; X3: Curing Level; X4: Shear Rate; X5: Shear Stress

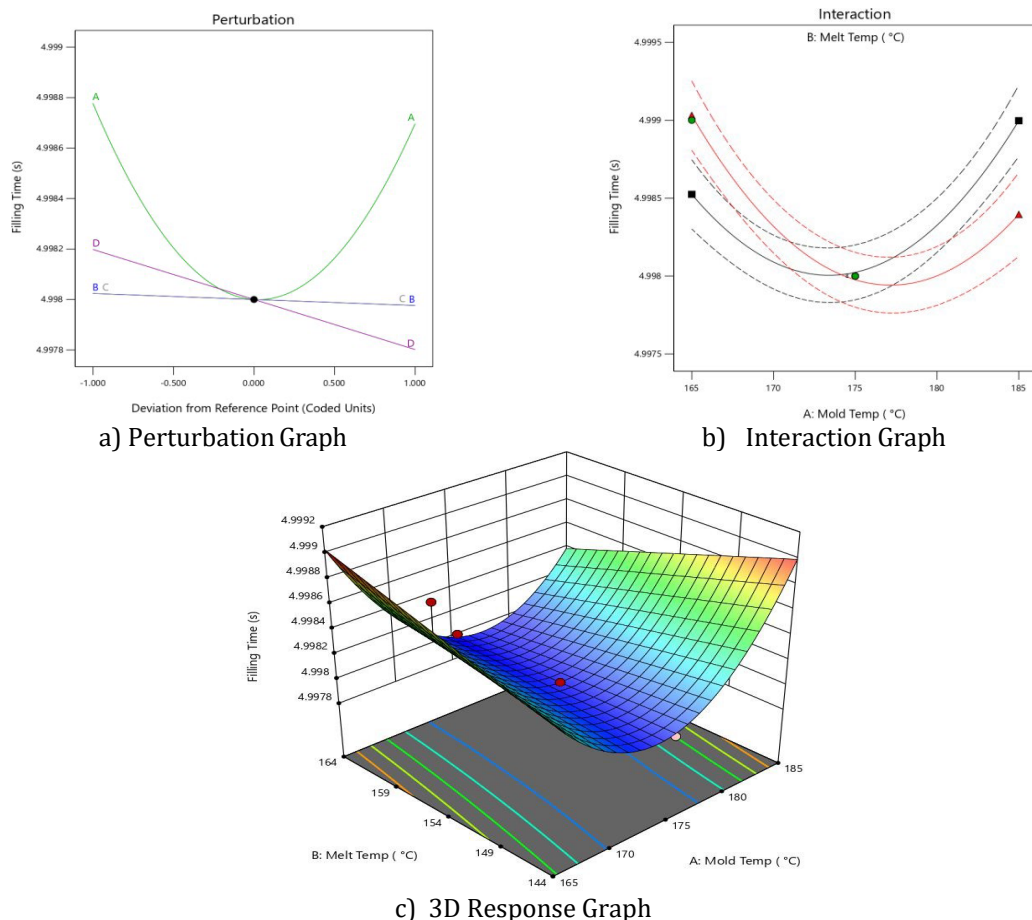
### 3. RESULTS AND DISCUSSION

Autodesk Moldflow Insight was used for simulating the transfer molding process, focusing on parameters such as mold temperature, melt temperature, curing time, and injection pressure. The simulation model includes variations in these parameters based on the Design of Experiments (DOE) methodology. Central Composite Design (CCD) is employed to systematically explore the effects and interactions between the selected parameters. A total of 30 simulation runs were conducted, generating data on responses including filling time, air-trap formation, curing level, shear rate, and shear stress, as shown in Table 5.

#### 3.1 Effect of factors on the response

##### 3.1.1 Filling time (s)

Figure 4 presents perturbation, interaction, and 3D surface plots in a single figure, showing how mold temperature (A), melt temperature (B), curing time (C = 30), and injection pressure (D = 180) affect filling time. mold temperature (A) has the most significant effect, with a clear non-linear relationship where filling time decreases initially as mold temperature increases, then increases again at higher temperatures. This suggests that higher mold temperatures reduce the polymer’s viscosity, allowing faster flow and easier filling up to a point. However, beyond that, the flow starts to stabilize, possibly due to the polymer’s rheological properties becoming more resistant at very high mold temperatures. In contrast, melt temperature, curing time, and injection pressure show relatively flat curves, indicating these factors have a smaller influence on filling time compared to mold temperature. These results align with previous findings, which showed that mold temperature to the dominant factor influencing the polymer’s flow behavior [3].

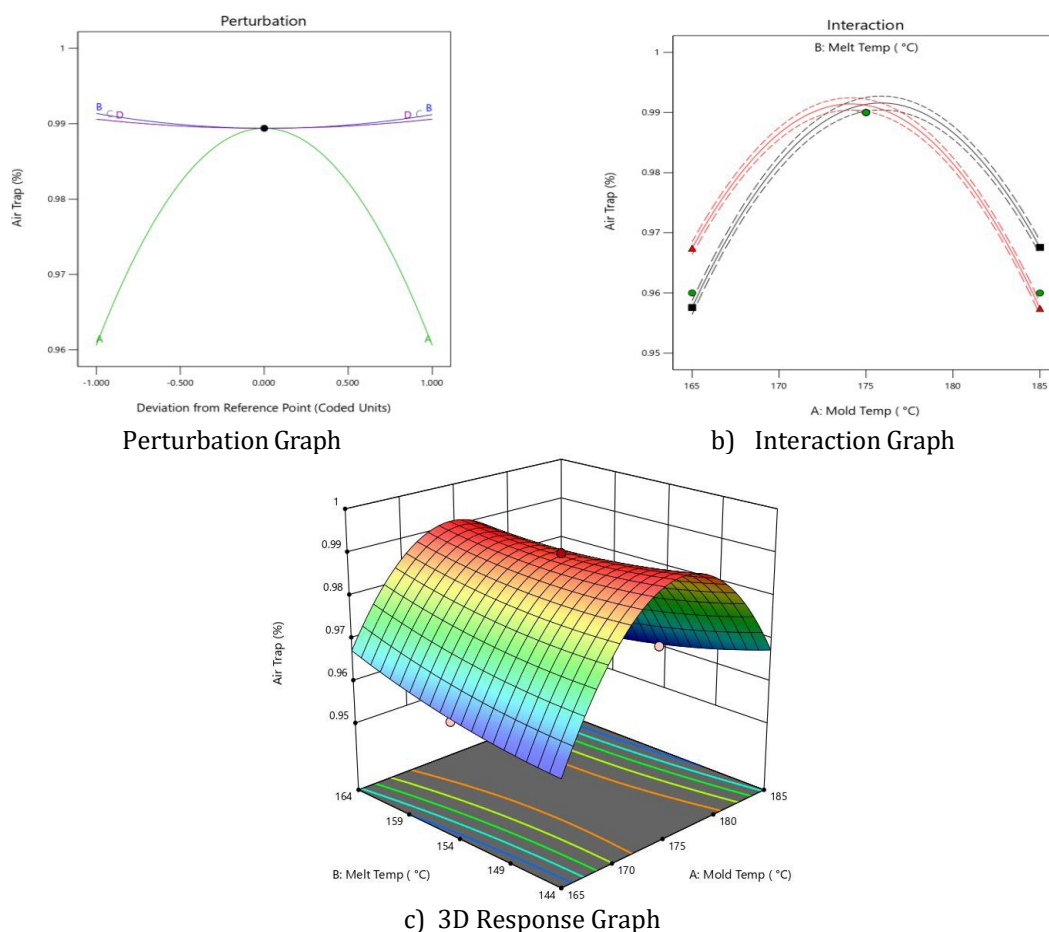


**Figure 4:** Filling time result analysis: a) Perturbation Graph, b) Interaction Graph and c) 3D Response.

The interaction plot confirms that mold temperature and melt temperature interact to affect filling time. As mold temperature increases, filling time decreases, particularly at higher melt temperatures, suggesting that increasing both mold and melt temperatures improves polymer flow by lowering viscosity. The 3D surface and contour plots show how mold and melt temperatures affect filling time. As mold temperature increases, polymer flow improves and filling time decreases. However, the effect of melt temperature is non-linear and depends on mold temperature, with higher melt temperature further reducing viscosity, particularly at lower mold temperatures. The contour patterns highlight regions where the polymer flow is less sensitive to temperature changes, indicating optimal filling time settings. The key finding is that mold temperature has the strongest effect on filling time, and its influence depends on melt temperature; suitable combinations of both improve polymer flow and reduce filling problems during the transfer molding process.

### 3.1.2 Air Trap (%)

Figure 5 presents perturbation, interaction, and 3D surface plots that demonstrate how mold and melt temperatures influence air trap (%), with curing time ( $C = 30$ ) and injection pressure ( $D = 180$ ) held constant. The perturbation plot shows that mold temperature has the greatest effect on air trap formation, with a nonlinear relationship. As mold temperature increases, air traps decrease to a certain point before rising again. This suggests that mold temperature affects the polymer's viscosity and flow properties, influencing air entrapment. In contrast, melt temperature, curing time, and injection pressure show minimal effects on air trap formation, indicating a lower impact on the material's flow and curing behavior. These results align with previous studies [8], which emphasized mold temperature as the key factor in controlling air trap formation.

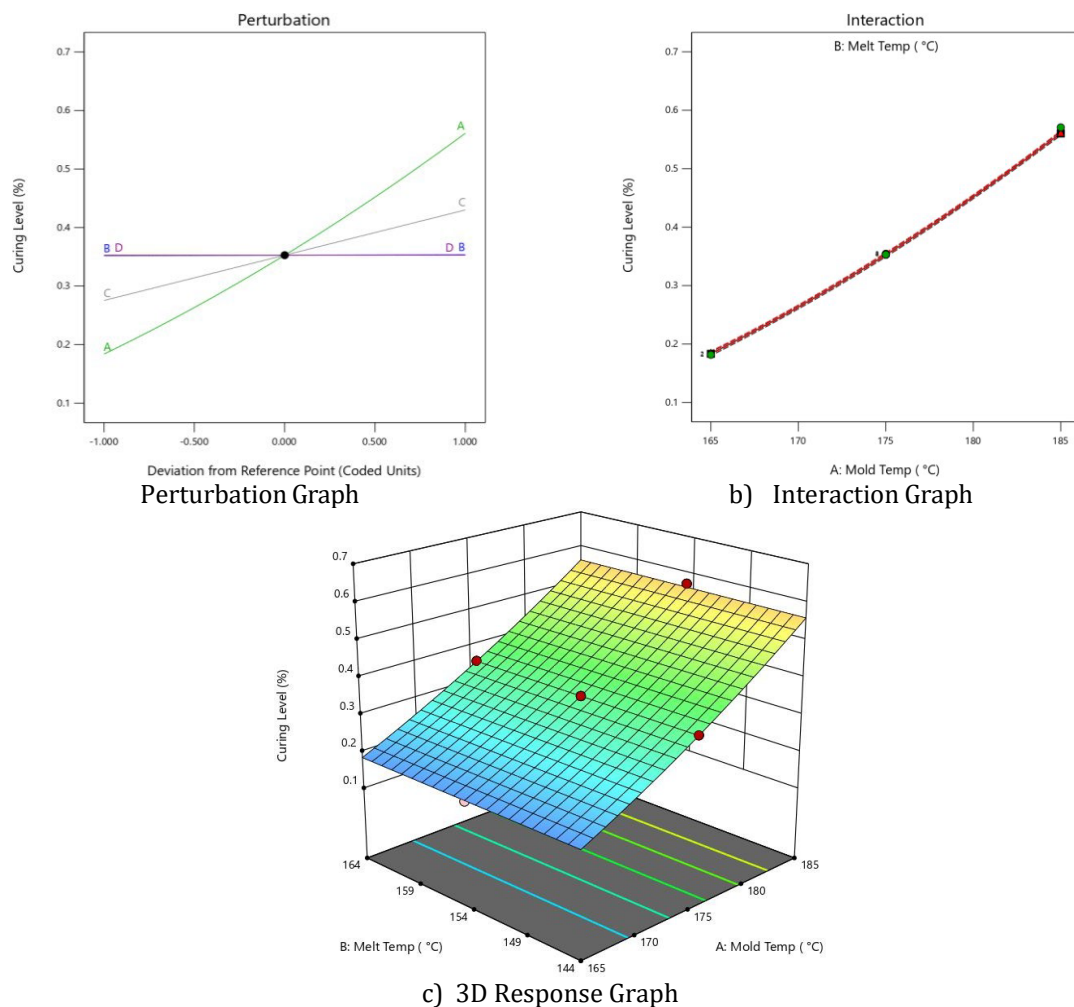


**Figure 5:** Air Trap result analysis: a) Perturbation Graph, b) Interaction Graph and c) 3D Response

The interaction plot further confirms that mold temperature and melt temperature interact to reduce air trap formation. As mold temperature increases, air trap decreases, especially at higher melt temperatures. The 3D surface plot shows that as both temperatures increase, air trap formation decreases, with mold temperature having the strongest effect on flow and curing. The contour patterns reveal regions where the polymer flow is less sensitive to temperature changes, indicating optimal settings for minimizing air trap formation. These findings support the critical role of mold temperature in controlling polymer rheology and the interaction with Melt Temperature to reduce air traps, as also noted in previous research [9]. The key finding is that mold temperature is the main factor affecting air trap formation, and its effect is enhanced by melt temperature, where well-controlled combinations of both improve polymer flow and reduce air entrapment during the molding process.

### 3.1.3 Curing Level (%)

Figure 6 presents perturbation, interaction, and 3D surface plots showing how mold temperature, melt temperature, curing time (C = 30), and injection pressure (D = 180) affect the curing level (%). Mold temperature has the largest effect, with curing level increasing as the temperature rises. This occurs because higher mold temperatures reduce polymer viscosity, improving flow and curing efficiency. Melt temperature and injection pressure have minimal impact, suggesting they don't significantly influence the flow or curing in this process. Curing time also has a small effect, but it is less significant than mold temperature, confirming mold temperature as the primary factor controlling curing behavior, consistent with findings by [9].

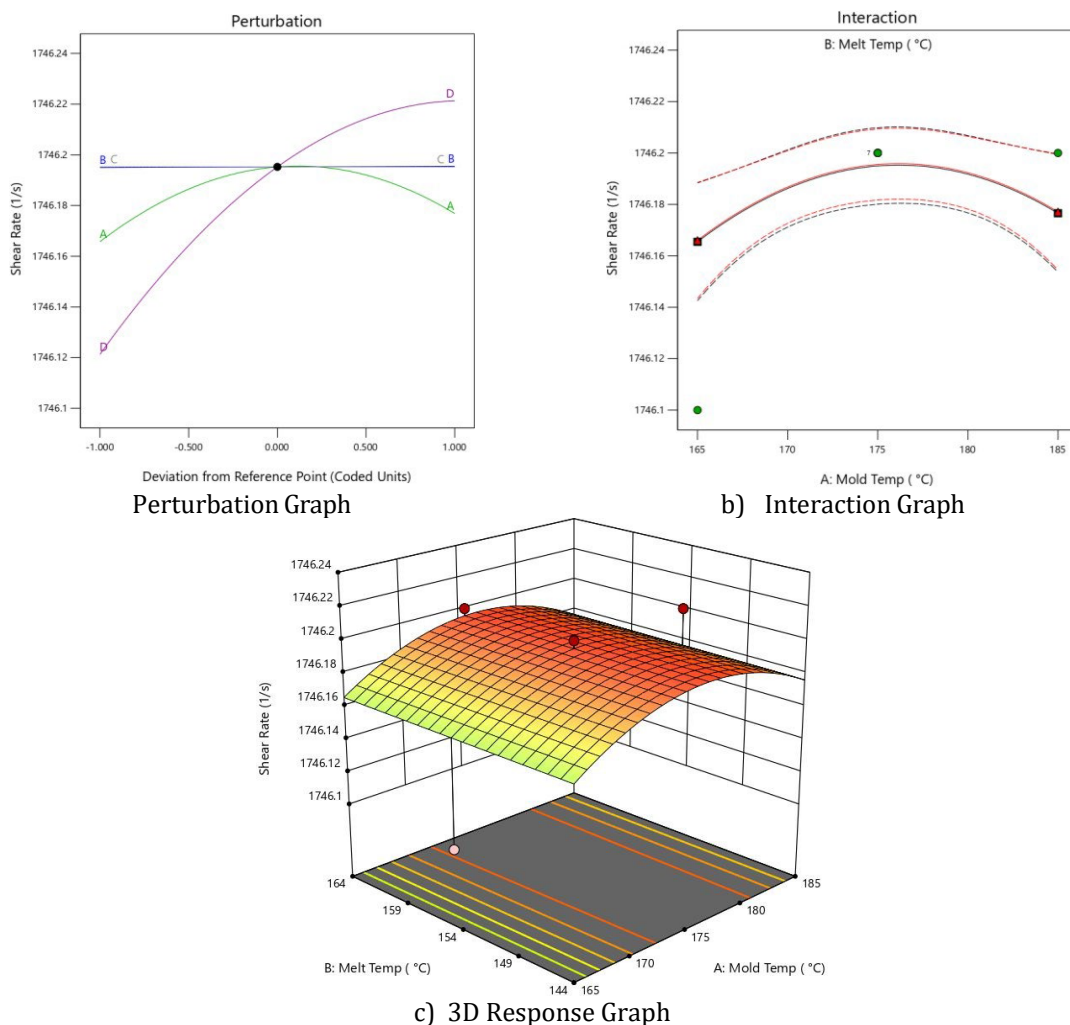


**Figure 6:** Curing Level result analysis: a) Perturbation Graph, b) Interaction Graph and c) 3D Response.

The interaction plot further emphasizes that as mold temperature increases, curing level (%) increases, especially at higher melt temperatures (B+164). The 3D surface plot confirms that increasing both mold temperature and melt Temperature results in a higher curing level, with better flow and curing observed at higher temperatures. The confidence intervals confirm these trends, showing that mold and melt temperatures consistently lead to higher curing levels, highlighting their role in controlling polymer rheology. The key finding is that mold temperature is the most influential factor in increasing curing level, with higher temperatures, supported by melt temperature, enhancing polymer flow and promoting more effective curing during the molding process.

### 3.1.4 Shear Rate (1/s)

Figure 7 presents the perturbation, interaction, and 3D surface plots, showing how mold temperature, melt temperature, curing time (C = 30), and injection pressure (D = 180) affect shear rate (1/s). Mold temperature (A) has the strongest effect, with shear rate increasing initially and then decreasing at higher mold temperatures. This suggests that higher mold temperatures reduce polymer viscosity, allowing easier flow up to a certain point. Melt temperature and injection pressure have smaller effects, indicating they don't significantly impact flow within the tested range. Curing time shows minimal influence, aligning with its role primarily in the curing phase after the polymer has flowed. These results are consistent with research by [8], who also found mold temperature to be the primary factor influencing flow behavior.

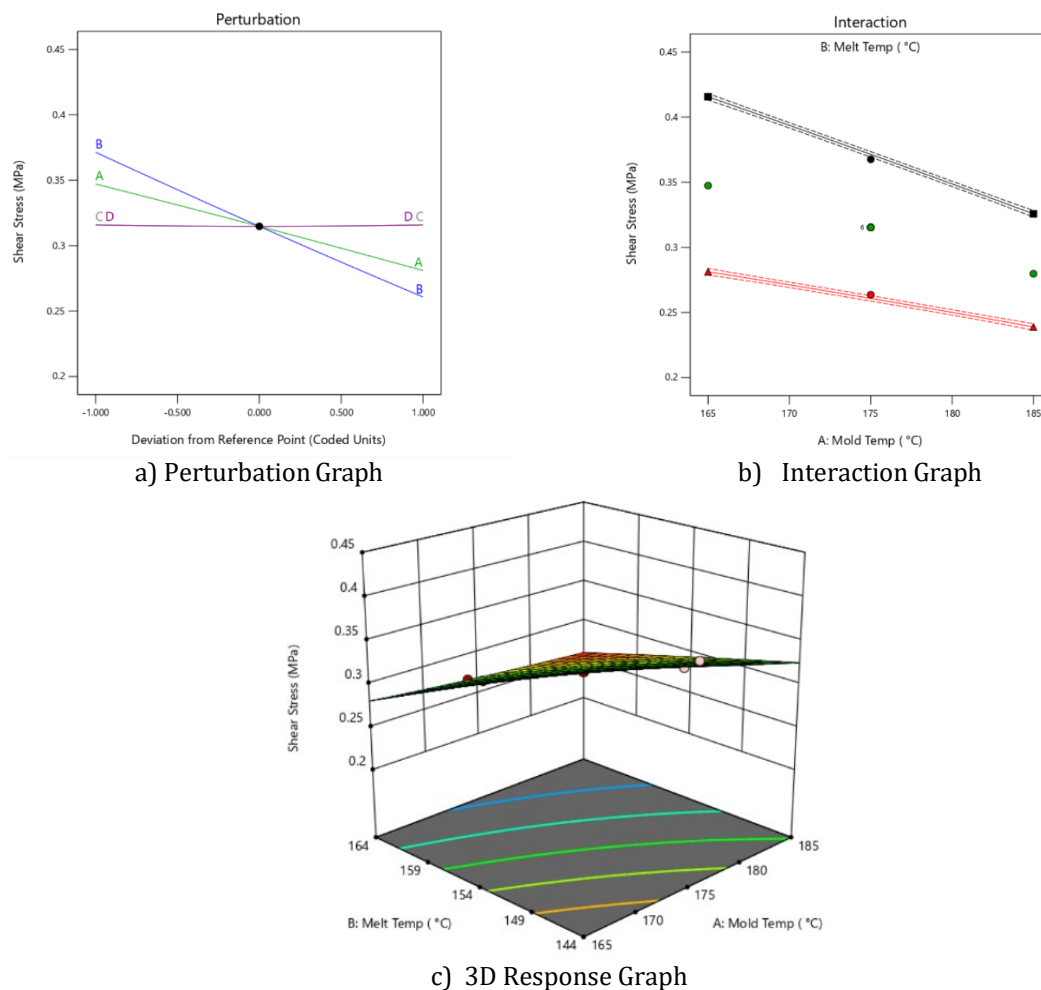


**Figure 7:** Shear Rate result analysis: a) Perturbation Graph, b) Interaction Graph and c) 3D Response.

The interaction graph further shows that mold temperature and melt temperature interact to affect shear rate (1/s), with higher mold temperature increasing shear rate more at higher melt temperatures. This indicates that both temperatures reduce viscosity, improving polymer flow. The 3D surface plot shows that shear rate increases with mold temperature up to a point, after which it stabilizes. Melt temperature has a stronger effect at lower mold temperatures, making the polymer flow more easily. These findings confirm that mold temperature and melt temperature are key factors in controlling polymer flow behavior, as highlighted by [10]. The key finding is that mold temperature is the dominant factor influencing shear rate, with its interaction with melt temperature significantly affecting the polymer flow and optimizing the molding process.

### 3.1.4 Shear Stress (MPa)

Figure 8 presents the perturbation, interaction, and 3D surface plots, showing how mold temperature, melt temperature, curing time (C = 30), and injection pressure (D = 180) affect shear stress (MPa). Melt temperature (B) has the strongest effect, decreasing shear stress as it increases, suggesting that higher melt temperatures reduce viscosity, making the polymer flow more easily. Mold temperature, on the other hand, increases shear stress as it raises viscosity, slowing the flow. Curing time and injection pressure have minimal effects, indicating they don't significantly impact shear stress within the tested range. These findings align with previous research [5, 6] and confirm that mold and melt temperatures are the primary factors controlling shear stress.



**Figure 8:** Shear Stress result analysis: a) Perturbation Graph, b) Interaction Graph and c) 3D Response.

The interaction graph further emphasizes the combined effect of mold temperature and melt temperature on shear stress (MPa). As mold temperature increases, shear stress decreases, especially at lower melt temperatures (B-144), where the effect is stronger. However, at higher melt temperatures (B+164), the effect of mold temperature weakens. The 3D surface plot shows that changes in these temperatures have minimal impact on shear stress within the tested range, with the polymer's flow behavior remaining stable. These results support earlier findings by [7], highlighting the relatively small impact of temperature changes on shear stress. The key takeaway is that shear stress is mainly governed by the combined effects of mold temperature and melt temperature, with melt temperature playing the dominant role in reducing shear stress.

### 3.2 Optimization of Process Parameters

Table 6 outlines the key parameters used for optimizing the injection molding process, including their goals, acceptable limits, and the importance of each in ensuring an efficient process and high-quality products. It lists factors such as Mold Temperature, Melt Temperature, Curing Time, and Injection Pressure, specifying the desired range for each, along with targets like minimizing filling time and air trap formation, and maximizing curing level and shear rate. These criteria are critical for guiding adjustments to improve the overall molding process and achieve optimal product quality and process efficiency.

**Table 6:** Criteria for Optimization.

Name	Goal	Lower Limit	Upper Limit
Filling Time	minimize	4.998	4.999
Air Trap	minimize	0.96	0.99
Curing Level	maximize	0.1284	0.6584
Shear Rate	maximize	1746.1	1746.2
Shear Stress	minimize	0.2407	0.4181

### 3.3 Validation of Results

Validation is the final step to ensure the accuracy of the optimization results. This is done by calculating the percentage difference between the predicted values from Design Expert and the simulation results from Moldflow. The predicted results are based on the optimal parameters suggested by Design-Expert, as shown in Table 7, while the simulation results are obtained by running simulations with the same optimal settings, as recorded in Table 7. The accuracy is assessed by calculating the percentage difference between the predicted and simulation results, as outlined by Equation (2). The validation is considered successful, as the percentage differences are minimal, confirming that the optimization model is reliable and the predicted values closely match the simulation results.

$$\text{Percentage of difference} = \frac{(\text{Predicted value} - \text{Simulation Value})}{\frac{(\text{Predicted value} + \text{Simulation value})}{2}} \times 100 \quad (1)$$

**Table 7:** Validation Result of Optimization.

Response	Unit	Value from RSM	Value from software simulation	Percentage difference (%)
Filling Time	s	4.998	4.998	0
Air Trap	s	0.96	0.96	0
Curing Level	%	0.658	0.6584	0.0607
Shear Rate	1/s	1746..203	1746.2	1.7179
Shear Stress	MPa	0.241	0.2407	0.1246

#### 4. CONCLUSION

This study successfully utilized simulation-based optimization to improve the plastic transfer molding process for Quad Flat No-Lead (QFN) encapsulation, focusing on optimizing key parameters to enhance product quality and process efficiency. The research evaluated the influence of mold temperature, melt temperature, curing time, and injection pressure on critical responses like filling time, air trap formation, curing level, shear rate, and shear stress. Using Response Surface Methodology (RSM) with Central Composite Design (CCD), the study identified optimal settings to achieve high-quality molded parts with minimal defects.

Key findings showed that mold and melt temperatures were the most influential parameters, affecting both filling time and air-trap formation. Higher mold temperature improved polymer flow and reduced viscosity, while higher melt temperature decreased shear stress, enhancing flow behaviour. Curing time and injection pressure had minimal impact on the responses, supporting the idea that temperature-related factors are the primary drivers in process optimization. The optimization process successfully minimized defects while maximizing curing levels, ensuring smooth flow and structural integrity in the final product.

The optimization results were validated by comparing Design Expert-predicted values with Moldflow simulation results, with differences well within the acceptable engineering threshold. This demonstrated the reliability and accuracy of the model. Overall, this study confirms that simulation-based optimization is an effective approach for enhancing the plastic transfer molding process, with applications in QFN packaging and similar semiconductor manufacturing processes.

#### ACKNOWLEDGEMENTS

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#### **Declaration of Generative AI Use**

In this work, the authors utilized AI tool to assist with initial literature exploration and to structure the research framework. The authors subsequently conducted a full review, validated all sources, and take full responsibility for the final intellectual content.