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Investigation of Significant Parameter and Interaction of Plastic Transfer Molding Parameters for 3D Dual In-Line IC Package Encapsulation

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ABSTRACT

Control of plastic transfer molding process parameters is critical to ensure high yield and part reliability in advanced semiconductor packaging. This paper investigates the parameters influencing air bubble formation and shear stress in the 3D Dual In-Line Package (DIP) encapsulation. To separate out these effects, Mold-flow® simulation was conducted at different processing parameters, namely mold temperature, melt temperature, curing time and injection pressure. The experiment also differentiated the material formula between un-filled and 80% silica-filled epoxy molding compound (EMC). ANOVA-based response surface methodology (RSM) was used to assess the significance and interactions of these parameters. The results indicate that process sensitivity is tightly dependent on the silica filler content (F > 900, p < 0.0001). The unfilled EMC exhibited steady performance, with minimal variation of defects regardless of processing modifications. However, the trend in highly filled EMC is triply diphasic, with the dip as its highest is driven by high viscosity. Among the factors that could be controlled the most, there is the melt temperature that is the most effective way to reduce the air traps and shear stresses (p < 0.0001). The contribution of a mold temperature to a predictable, synergistic, secondary effect was noted. Based on this analysis, a process window was designed for the processing of high filler EMC with high melt and mold temperature and sufficient injection pressure. The developed statistical models have been shown to be highly predictive (R^2 > 0.96, adequate precision > 37). By elucidating these material–process–defect relationships, this work presents a clear-cut dual-defect mitigation technique for enhanced yield, reduced rework and reliable high-density electronic system outcomes.

Keywords: *Plastic Transfer Molding, 3D Dual In-Line Package, Encapsulation, Air Trap, Shear Stress, Design of Experiments*

1. INTRODUCTION

3D DIPs (three-dimensional dual in-line packages) have been the most popular packaging for semiconductors due to the excellent mechanical strength, thermal characteristics, and high-density integration. Their stacked arrangement as in Fig. 1 enhances the functional density, but also results in geometric complexity, then uniform encapsulation along with defect avoidance becomes difficult [1,2]. Plastic Transfer Molding (PTM) continues to be the prevailing packaging technology, where the processing conditions including mold temperature, melt temperature, curing time, injection pressure and material composition have significant effect on the flow of resin, curing, and defect generation [3–5].

Among the concerns are the formation of air traps, which weaken the interface and allow moisture ingression, and under curing, which degrades thermal and mechanical properties [2,4]. Such defects are often caused by interaction of parameters, i.e., low melt temperature and high injection pressure, or curing time and mold temperature [1,3]. Progress in numerical simulation especially mold flow analysis now allows prediction of flow, defect regions, and parameter importance without a large number of experimental works [1,2,5]. Statistical DoE designs, when used along wit these tools, will provide a comprehensive evaluation of PTM process variables. This study applies a simulation-based design of experiment (DoE) to identify the key parameters and interactions of PTM affecting the quality of 3D DIP encapsulation with special consideration of air trap formation and shear stress, and thus contributes to minimizing defects and maximizing reliability in semiconductor packaging.

2. LITERATURE REVIEW

New developments in encapsulation are challenging PTM parameters to be optimized for 3D DIPs. Sousa et al. (2025) applied transient 3D process simulations of non-isothermal transfer molding by means of porous media modeling, illustrating the significance of thermal–flow interaction in fill behavior prediction [6]. Phansalkar et al. (2022) reviewed important thermomechanical properties of EMCs and emphasized their influence on warpage and stress analysis [7]. Park et al. (2023) at a modified cure cycle with rapid cooling yielded 26% less residual strain and 27% less curvature for EMC/Cu bilayers [8]. Achor (2024) simulated injection molding of a water-filter handle to illustrate how fill dynamics, temperature, and gate location influence defects [9]. Together, these studies highlight the necessity of coupled simulation–experimental strategies to capture parameter interactions.

On the basis of this line of work, the current study modifies and expands the work of Sousa et al. (2025) to consider non-isothermal flow and thermal–flow coupling (not only thermal conduction and convection), curing kinetics (not only thermal kinetics) within a holistic DoE-based simulation approach [6]. Unlike Park et al. (2023) [8], which focused primarily on the adaptiveness of cure cycles to reduce the residual strain, this work addresses mold temperature, melt temperature, injection pressure, curing time, and material formulation to study their combined impact on the formation of air traps and shear stress. This combination enables the encapsulation process behavior to be better understood for 3D DIP geometries, which currently is a gap in simulation studies.

3. METHODOLOGY

The present study develops a simulation-based optimization scheme to improve the plastic transfer molding process for 3D Dual In-line Package (DIP) encapsulation. A 3D Dip (dual in-line package) model which consists of the lead frames, cavity, runners, gavits was designed using industrial standard dimension in SolidWorks and the analysis was conducted by using Moldflow in Autodesk. We validated the mesh quality based on the statistical tools and the influence of the global edge length of 0.7 mm which compromises the efficiency is acceptable for the resolution. The mesh consists of 9617 triangular elements and 4816 nodes with an aspect ratio of 1.16–5.12 a surface area of 15.907 cm 2 and a volume of 1.61 cm 3. The mesh size and number of elements for the proposed Telsa inverter model are chosen based on mesh convergence analysis to get an appropriate trade-off between the computation cost and accuracy of the solution. The edge analysis yielded 14,460 manifold edges without irregularities, so resulting in a test coverage (that is, pairwise mesh protocol) of 93.3% with 95.3% reciprocal accuracy, which guaranteed a few reliable simulation results. To statistically confirm the influence of the process parameters, the simulation results are analysed using analysis of variance (ANOVA). The parameters studied were mold temperature, melt temperature, injection pressure, curing time and material formulation. Significance was assumed at the 95% confidence level, and p-values < 0.05 were considered statistically significant. This study measures the relative impact and synergy of each parameter one shear stress and the formation of air traps.

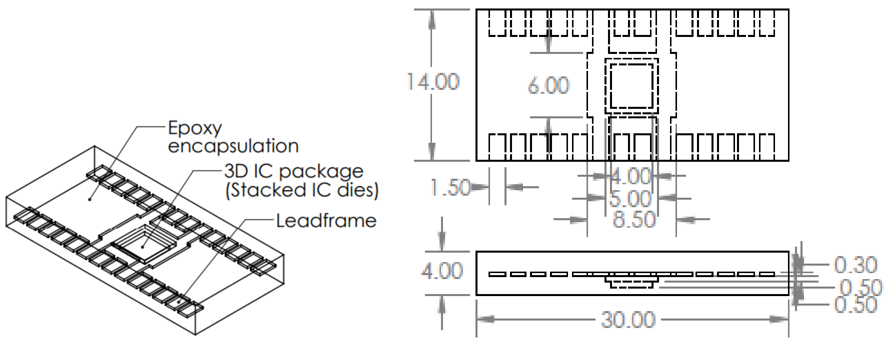


Figure 1. Dimension of 3D Dual In-line Package (mm) document.

3.1 Material Selection

Two EMCs (Table 2) were employed: Material A without filler and Material B with >80% silica filler. Both were processed at a melt temperature of 65 °C (range 50–80 °C) and a mold temperature of 170 °C (range 160–180 °C), utilizing an ejection conversion factor of 0.5. The high silica content in Material B enhances the thermal conductivity [10], decreases the CTE leading to better dimensional stability [13], as well as the modulus and the hardness [11], viscosity is increased, which impedes flow, and may result in voids [12]. The increase in viscosity at high loading can be reduced by employing smaller silica particles [14]. Herein, we present a study comparing unfilled and filled EMC under identical conditions to isolate the effects of silica on flow, voiding, pressure, and thermal uniformity in 3D DIP encapsulation.

3.2 Selection of Influential Factors and Responses

The design of experiments in Table 1 involved four numerical factors: mold temperature, melt temperature, curing time, injection pressure, and one categorical factor, the material type. The numerical factors were performed at three levels: mold temperature (160–180 °C), melt temperature (50–80 °C), curing time (24–36 s), and injection pressure (144–216 MPa). Levels were established based on preliminary experiments and literature io represent a typical processing range.

Table 1 Levels of processing parameters

Factor	Level		
	L1	**L2**	**L3**
A: Mold temperature, ℃	160	170	180
B: Melt temperature, ℃	50	65	80
C: Curing time, s	24	30	36
D: Injection Pressure (MPa)	144	180	216
E: Material	A	B	

A response surface methodology (RSM) was applied to evaluate the effects of 5 factors (mould temperature, melt temperature, cure time, injection pressure, and material type) on air trap formation and shear stress using a custom design of experiments (DoE) with 60 simulation runs. Analysis of variance (ANOVA) was performed at 95% confidence level (α=0.05) by means of the Design-Expert statistical package. Model validity was checked through the R^2, adjusted R^2 and predicted R^2 values, the lack-of-fit tests and the adequate precision ratios. Non-significant terms (p>0.10) were removed stepwise to yield reduced models with respect to maintaining hierarchical structure. The high closeness of predicted and adjusted R^2 (<0.2 difference) and adequate precision ratios higher than 35 also ensure that either model is strong and the design space can be pursued safely.

4. RESULT AND DISCUSSION

The full-factorial design matrix, along with the simulation results from all 60 runs that explain the influence of five process parameters on air trap generation and shear stress in 3D DIP encapsulation, is given in Table 2. The design uses four numerical factors, mold temperature (160–180 °C), melt temperature (50–80 °C), curing time (24–36 s), and injection pressure (144–216 MPa) and one categorical factor (material type: A for unfilled EMC and B for 80% silica-filled EMC). Upon inspecting the response data two clear behavioral regimes can be identified between the two materials: Material A (unfilled) had a process insensitivity due to its low viscosity as it always had an air trap percentage of 0.99 % and the shear stress was virtually zero (~0.08 MPa) for all parameter combinations. Conversely, Material B (silica-filled) showed significant variation, the air trap ranging from 0.91% to 0.94% and the shear stress from 0.41 to 2.68 MPa, indication of sensibility to processing conditions. This combined data set is the basis for ANOVA and response surface optimization, so that the effects of each factor, interactions mechanisms between factors and optimum parameter combinations that minimize the defect in high density semiconductor packaging ap-plications can be quantified.

Table 2 Result of experimental design matrix and simulation

Run	Factors					Responses	
	A	**B**	**C**	**D**	**E**	**Air trap, %**	**Shear stress, Mpa**
1	160	50	24	144	A	0.99	0.0802
2	180	80	36	144	B	0.93	0.4111
3	160	50	24	216	B	0.91	2.679
4	170	65	30	180	B	0.94	1.018
5	180	50	36	144	A	0.99	0.0802
6	180	50	36	144	B	0.93	1.353
7	170	65	36	180	A	0.99	0.0802
8	160	65	30	180	B	0.94	1.414
9	170	65	30	180	B	0.94	1.018
10	170	65	30	216	B	0.94	1.018
11	180	80	36	216	A	0.99	0.0802
12	180	50	36	216	B	0.93	1.353
13	170	65	30	180	A	0.99	0.0802
14	160	50	36	216	A	0.99	0.0802
15	160	80	24	216	B	0.94	0.763
16	180	80	24	216	A	0.99	0.0802
17	180	80	36	144	A	0.99	0.0802

18	160	80	36	216	B	0.94	0.763
19	170	65	30	180	B	0.94	1.018
20	180	80	36	216	B	0.93	0.4111
21	180	65	30	180	A	0.99	0.0802
22	180	50	24	144	B	0.93	1.353
23	160	65	30	180	A	0.99	0.0802
24	160	50	24	144	B	0.91	2.679
25	170	80	30	180	A	0.99	0.0802
26	170	80	30	180	B	0.94	0.5583
27	170	50	30	180	B	0.92	1.896
28	180	50	24	216	B	0.93	1.353
29	170	65	30	180	A	0.99	0.0802
30	170	65	30	180	A	0.99	0.0802
31	160	80	24	144	B	0.94	0.763
32	160	80	36	216	A	0.99	0.0802
33	160	50	36	144	A	0.99	0.0802
34	170	65	24	180	B	0.94	1.018
35	170	65	30	144	A	0.99	0.0802
36	160	50	36	144	B	0.91	2.679
37	170	50	30	180	A	0.99	0.0802
38	160	50	36	216	B	0.91	2.68
39	180	80	24	216	B	0.93	0.4111
40	160	80	24	144	A	0.99	0.0802
41	170	65	36	180	B	0.94	1.018
42	160	80	36	144	B	0.94	0.763
43	180	50	36	216	A	0.99	0.0802
44	160	50	24	216	A	0.99	0.0802
45	180	65	30	180	B	0.93	0.7375
46	180	80	24	144	B	0.93	0.4111
47	170	65	30	180	B	0.94	1.018
48	170	65	30	180	A	0.99	0.0802
49	180	80	24	144	A	0.99	0.0802
50	180	50	24	216	A	0.99	0.0802
51	170	65	30	180	B	0.94	1.018
52	180	50	24	144	A	0.99	0.0802
53	170	65	30	180	B	0.94	1.018
54	170	65	30	144	B	0.94	1.018
55	170	65	24	180	A	0.99	0.0802
56	170	65	30	180	A	0.99	0.0802
57	170	65	30	180	A	0.99	0.0802
58	160	80	24	216	A	0.99	0.0802
59	170	65	30	216	A	0.99	0.0802
60	160	80	36	144	A	0.99	0.0802

A: Mold temp
B: Melt temp
C: Curing time
D: Injection Pressure
E: Material

4.1 Response 1: Air Trap

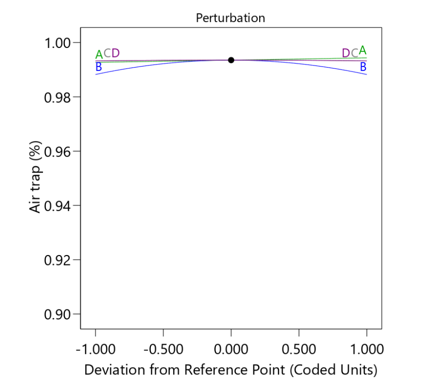
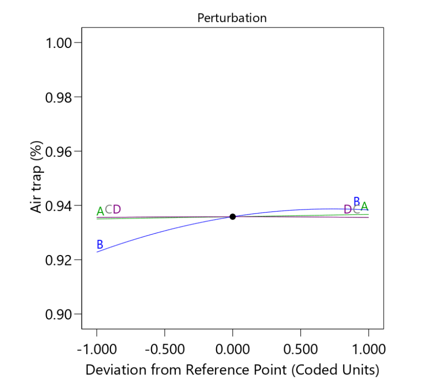
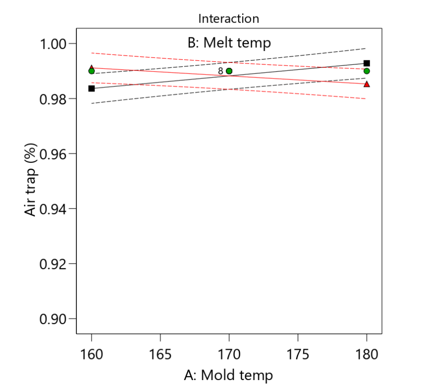
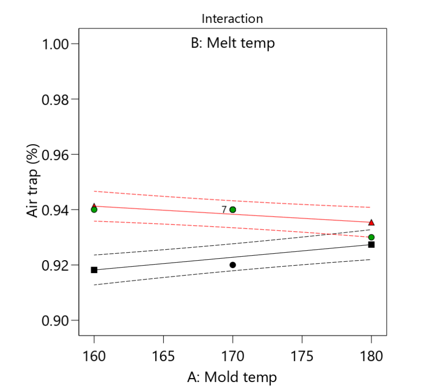
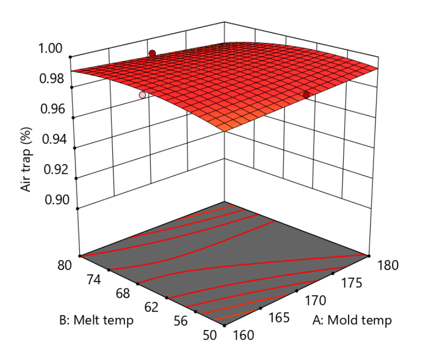
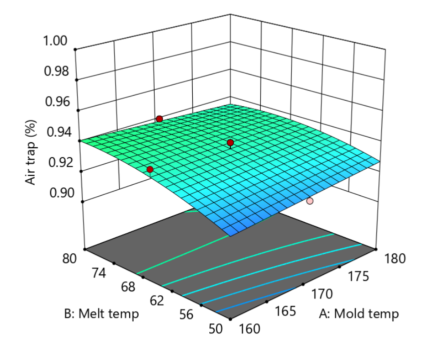
Reduced quadratic model Air trap formation The reduced quadratic model for the air trap formation in Table 3 is very significant (F = 230.36, $p < 0.0001$) with material composition (E) and melt temperature (B) as the most influential variables ($p < 0.0001$), followed by significant AB and BE interactions as well as the quadratic melt temperature term (B^2). The adequacy of the model could be ascertained through the satisfactory goodness of fit statistics R^2 = 0.9792, adjusted R^2 = 0.9749, predicted R^2=0. 9682 (difference < 0.2) and adequate precision = 37.74 (> 4 limit). These statistics confirm the model's strength and predictability for the process parameters, therebyreducinge air-trap defects in 3D DIP encapsulation.

Table 3 ANOVA Summary for Air Trap Response (Reduced Quadratic Model)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.0519	10	0.0052	230.36	< 0.0001
A-Mold temp	0	1	0	1.11	0.2974
B-Melt temp	0.0005	1	0.0005	24.16	< 0.0001
C-Curing time	0	1	0	0	1
D-Injection Pressure	0	1	0	0	1
E-Material	0.0499	1	0.0499	2213.44	< 0.0001
AB	0.0004	1	0.0004	19.97	< 0.0001
BE	0.0005	1	0.0005	24.16	< 0.0001
B^2	0.0002	1	0.0002	7.03	0.0107
C^2	4.58E-07	1	4.58E-07	0.0203	0.8872
D^2	4.58E-07	1	4.58E-07	0.0203	0.8872
Residual	0.0011	49	0		
Lack of Fit	0.0011	39	0		
Pure Error	0	10	0		
Cor Total	0.053	59			
Std. Dev.	0.0047		R^2	0.9792	
Mean	0.9612		Adjusted R^2	0.9749	
C.V. %	0.4939		Predicted R^2	0.9682	
			Adeq Precision	37.741	

From Table 4, a strong dependence of air trap formation on material composition was observed. For unfilled EMC, air traps were not affected significantly by mold temperature, melt temperature, curing time, or injection pressure due to its low viscosity and stable filling behaviors. Conversely, the highly filled EMC was much more sensitive, and the reduction of air traps due to the improvement of flow and compaction as a result of higher melt temperature and injection pressure was more noticeable [15]. The interaction analysis also showed a slight interaction effect of Tg between them in the unfilled EMC; however, they exerted a significant synergistic effect in the filled system. The maximum reduction in air trap percentages could be obtained when both parameters were increased simultaneously, as the combined thermal energy input compensated for the viscosity-increasing effect of the filler and led to an adequate filling of the cavity [16]. These findings define a proper process window for filled EMC, showing that an approach based on strategic combinations of parameters is required to minimize the air trap defects.

Table 4 Perturbation plot and interaction graph result of Air Trap

Pertubation Plot		
Interaction Graph		
Response Surface		
	Material A (No filler)	Material B (80% Silica Filled)

The 3D response surfaces for air trap formation versus mold and melt temperature at a set curing time (30 s) at an injection pressure of 180 MPa. The dramatic difference between Material A (unfilled) and Material B (80% silica-filled) visually confirms the strongest effect-of-composition result obtained from the ANOVA (F=2213.44, p<0.0001). In the case of unfilled EMC, the flat, nearly horizontal surface signifies "process insensitivity," indicating that air traps remain constant at ~0.99% regardless of thermal conditions. On the contrary, a rather sloped surface is observed in the filled EMC, with the percentage of air traps reducing from 0.96% to 0.91% as both temperatures increase. This 5% relative improvement achieved by combined thermal management isae manifestation of significant AB (F=19.97, p<0.0001) and BE (F=24.16, p<0.0001) interactions. The shallow contour lines along the side of the melt temperature axis are also evidence that this is the most important adjustable factor; the diagonal pattern of lines suggests that higher temperatures for both are needed for best-fill EMC. These results establish a sophisticated process window (Mold Temp ≥175 °C, Melt Temp ≥70 °C) for defect suppression in high-density 3D DIP encapsulation.

4.2 Response 2: Shear Stress

The ANOVA results for the reduced 2FI model in Table 5 indicate that the regression model is statistically significant, with an F-value of 194.58 ($p < 0.0001$). This shows that there is less than a 0.01% chance that an F value this large could be due to noise, which affirms the robustness of the model.

The 95% level ($\alpha = 0.05$) significance analyses showed that the terms of the model significant to the cure behavior were mold temperature (A), melt temperature (B), material composition (E) and two-way interactions ($p < 0.0001$) among AB, AE, and BE. On the other hand, curing time (C) and injection pressure (D) had p-values greater than 0.99, suggesting little to no impact on shear stress within the examined ranges of these factors.

The adequacy of the model was confirmed by several fit statistics. The coefficient of determination, R2 = 0.9683%, shows that model encompasses 96.83% of the total variation in shear stress. The predicted R2 of 0.9523 is in reasonable agreement with the adjusted R2 of 0.9633 i.e. the difference is less than the limit of 0.2, indicating that the model can be used for prediction purpose without overfitting the data. Further, the Adequate Precision value is 45. 243 is also much greater than the desirable sufficient signal value of 4, showing a very good signal-to-noise ratio. These statistical measures collectively ensure that the proposed model may be effectively utilized for the purpose of prediction within the design space and for identifying process parameters which were optimum so as to minimize shear stress in 3D DIP encapsulation.

Table 5 ANOVA summary for Shear stress (2FI model)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	30.94	8	3.87	194.58	< 0.0001
A-Mold temp	1.52	1	1.52	76.29	< 0.0001
B-Melt temp	4.53	1	4.53	227.88	< 0.0001
C-Curing time	2.78E-08	1	2.78E-08	1.40E-06	0.9991
D-Injection Pressure	2.78E-08	1	2.78E-08	1.40E-06	0.9991
E-Material	18.38	1	18.38	924.43	< 0.0001
AB	0.4747	1	0.4747	23.88	< 0.0001
AE	1.52	1	1.52	76.29	< 0.0001
BE	4.53	1	4.53	227.88	< 0.0001
Residual	1.01	51	0.0199		
Lack of Fit	1.01	41	0.0247		
Pure Error	0	10	0		
Cor Total	31.96	59			
Std. Dev.	0.141		R^2	0.9683	
Mean	0.6336		Adjusted R^2	0.9633	
C.V. %	22.25		Predicted R^2	0.9523	
			Adeq Precision	45.2426	

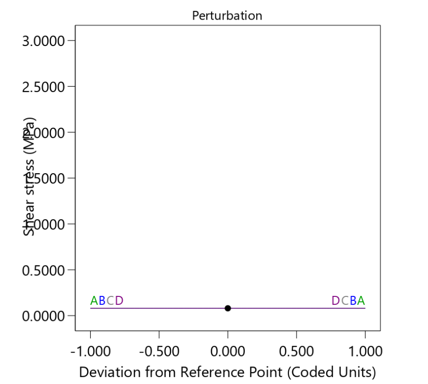
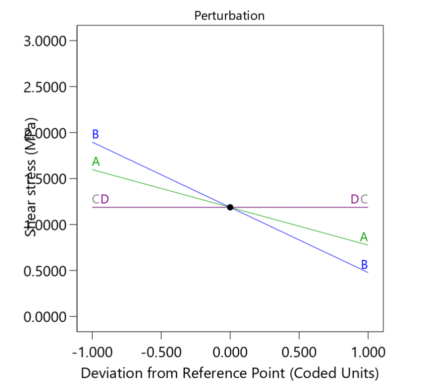
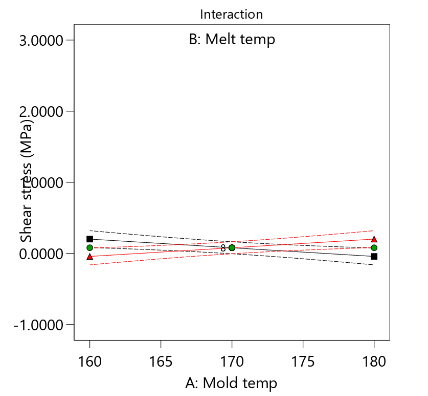
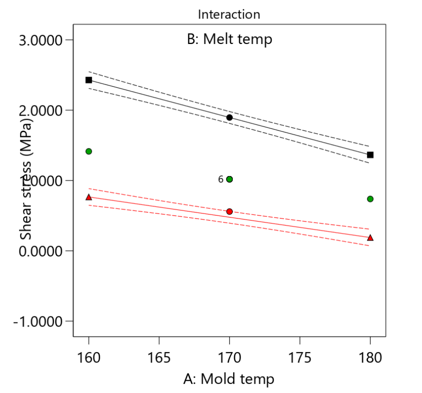
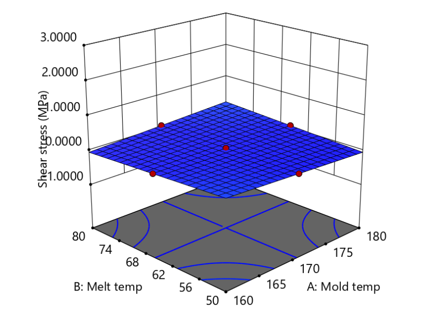
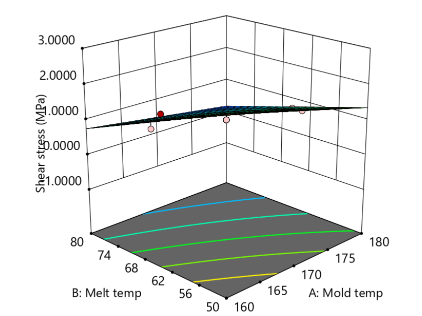
It can be observed from Table 6 that the shear stress in transfer molding is greatly impacted by the silica filler amount. In Material A (no filler), the shear stress was low (~0 MPa) and not affected by the mold temperature, melt temperature, cure time, or filling pressure. In sharp contrast, Material B (80% silica) had significantly larger shear stresses which were strongly influenced by melt temperature: stress was dramatically decreased by increasing the melt temperature due to a reduction in viscosity while much smaller reductions were obtained with the mold temperature.

Interaction plots confirmed these trends. Material A: shear stress was constant and low at approximately 0.08 MPa in all tested conditions. In Material B, shear stress varied from~0.08 to 2.68 MPa, for which very steep gradients were observed. Increasing melt temperatures consistently decreases shear stress at all mold temperature levels, and increasing mold temperature reduced but also enhanced the effect.

Taken as a whole, these results illustrate that unfilled EMCs indeed have low shear forces by nature, while extremely filled compounds are quite sensitive to optimal melt and mold temperatures to ensure low shear forces and process stability. Mold temperature (A) and melt temperature (B) were the foremost thermal parameters for the shear stress ($p<0.01$), and the air trap volume was mainly influenced by the injection pressure and melt temperature ($p<0.05$). The confidence intervals for each factor are tight enough to support these trends and indicate that the differences are statistically significant and not due to simulation variability.

These results confirm the sensitivity trends observed in previous studies, but provide more detailed statistical insight into a coupled 3D DIP encapsulation scenario. Table 4 shows the 3D response for shear stress versus mold temperature and melt temperature. For the unfilled EMC (Material A), the surface is flat and low (~0.08 MPa), indicating little sensitivity to thermal changes and very little shear hazard. In contrast, the response surface for the filled EMC (Material B) is very responsive with a shear stress maximum of 2.68 MPa at a low temperature (50°C melt / 160°C mold). This maximum corresponds to the region of high viscosity in the silica-filled compound. At a melt temperature of 80°C, shear stress decreases drastically to ~0.41 MPa (>80% reduction). This is consistent with the results of the ANOVA, since the significant thermal contributors were the Melt Temperature (F=227.88) and Mold Temperature (F=76.29). The sharp slope in the melt temperature confirms that this is the strongest single knob for controlling shear-related defects (such as wire sweep) in high-density packages. In addition, the surface curvature also indicates a significant AB interaction (testing p < 0.0001); this indicates that a joint increase in the two temperatures is necessary to significantly break down the filler network viscosity and reduce the mechanical stress on the encapsulated parts.

Table 6 Perturbation plot and interaction graph result of Shear Stress

Perturbation Graph		
Interaction Graph		
Response Surface		
	Material A (No filler)	Material B (80% Silica Filled)

4.3 Optimization of Process Parameters

This part is mainly concerned with process parameter optimization of 3D DIP encapsulation in order to reduce the amount of defects and improve productivity. Higher shear rates also result in more effective filling of the cavity and can help eliminate hesitation regions, which could be sites for air entrapment. The numerical optimization objectives and the resulting process parameters are tabulated in Tables 7 and 8. Based on the experiments, all continuous parameters were restricted within the ranges of experiment with minimized air traps (target: 0.91-0.99%) and maximized shear stress (target: 1356.4-2336.8 s -1) for the best cavity filling. The maximum desirability was calculated as 1.0, and based on the current investigation, the best setting is selecting Material A with a mold temperature of 168.33 °C, melt temperature of 79.998 °C, curing time of 36 s and injection pressure of 216 MPa. At these operating parameters, the model estimates a shear stress of 2336.81 s^{-1} and an air trap of 0.988%. This means that unfilled EMC is already close to the dual goal, with almost no adjustment to the thermal processing window, while high-filler compositions will require more stringent temperature control to balance flowability and defect mitigation.

Table 7 Criteria for optimization

Name	Goal	Lower Limit	Upper Limit
A: Mold temp	is in range	160	180
B: Melt temp	is in range	50	80
C: Curing time	is in range	24	36
D: Injection Pressure	is in range	144	216
E: Material	is in range	A	B
Air trap	minimize	0.91	0.99
Shear stress	maximize	1366.4	2336.8

Table 8 Suggested optimal value for each factor and response

Process Settings	Unit	Suggested Optimal Value
A: Mold temp	°C	168.326
B: Melt temp	°C	79.998
C: Curing time	s	36
D: Injection Pressure	MPa	216
E: Material		A
Air trap	%	0.988
Shear stress	1/s	2336.81

4.4 Validation of Results

Predictions are validated to check the trustworthiness of the optimization results by comparing the responses with the related simulation results. The predicted values resulted from the optimal solutions produced by the Design-Expert software (Table 7). Equation (1) is used to calculate the percentage deviation between predicted and simulated results, and the result is reported in Table 9. The validation is accepted because the observed percentage difference is small, indicating that the predicted and simulated data are in good agreement. The percentage difference is calculated using the formula:

$$Percentage\ different = \frac{|Predicted\ value - Simulation\ Value|}{\left(\frac{Predicted\ value + Simulation\ value}{2}\right)} \times 10 \qquad (1)$$

Table 9 Validation results of optimization

Response	Unit	RSM result	Simulation result	Percentage diff (%)
Air trap	%	0.988	0.982	0.6091
Shear stress	1/s	2336.81	2335.5	0.0560

The validation results confirm the reliability of the optimisation model, with percentage differences across all responses within tolerance. The air trap percentage shows a minor variation of 0.6%, indicating the model's ability to accurately predict defects. Although there is a 0.05% difference in shear stress, it is still sufficient to maintain continuous flow. Both solutions agree well, with a difference of less than 1% in the percentages, thus confirming the predictive capability of the model. These results validate the accuracy and robustness of the model and hence make it a reliable tool for cost-effective 3D DIP encapsulation with minimum errors.

5. CONCLUSION

In this research, a set of parameters and interactions in plastic transfer molding for encapsulation of 3D Dual In-Line Package (DIP) was investigated with respect to air trap and shear stress behavior. Dominant factor among them was the silica filler content ($F > 900$, $p < 0.0001$), unfilled EMC was able to remain stable toward all kinds of parameters, but the highly filled EMC was greatly influenced due to its very high viscosity. Melt temperature was the most significant controllable parameter to reduce both defects ($p < 0.0001$), mold temperature was a minor but synergistic contributor. Curing time and injection pressure had insignificant effects on both responses within the selected ranges. High performance was obtained for the highly filled EMC at high melt and mold temperatures (≥175°C and ≥70°C, respectively), and a narrow process window was identified for balancing the flow-ability and the defect suppression. Reliable statistical models ($R^2 > 0.96$, Adeq Precision > 37) were validated with <1% prediction error. The results suggest a dual-defect sensitivity mitigation method that significantly improves yield, reduces rework, and increases reliability in advanced electronic packaging. By linking material composition to precise thermal process control, this work presents a scientific methodology and practical recommendations for high-filler EMC encapsulation without defects.

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