

Optimization of Injection Moulding Parameters for Virgin and Hybrid ABS Composites Using Taguchi L₂₇ Orthogonal Array

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Abstract- In this study, the optimization of key injection moulding process parameters was carried out for both virgin and hybrid Acrylonitrile Butadiene Styrene (ABS) composites. Hybrid composites were reinforced with glass fiber and granite powder to enhance mechanical performance and dimensional stability. A Taguchi L₂₇ orthogonal array was employed to systematically investigate the influence of six critical factors mould temperature, melt temperature, injection pressure, packing time, packing pressure, and cooling time on shrinkage, warpage, and compressive strength. The signal-to-noise (S/N) ratio and analysis of variance (ANOVA) were used to identify the most influential parameters. Confirmation experiments were conducted to validate the optimized settings, revealing a significant improvement in performance characteristics for both virgin and hybrid ABS components. The findings provide valuable insights for manufacturers aiming to reduce defects and improve the mechanical integrity of ABS moulded parts.

Keywords: Injection Moulding, ABS Composites, Taguchi Method, Shrinkage, Warpage, Compressive Strength, Process Optimization

I. INTRODUCTION

Injection moulding is a widely adopted manufacturing process for producing complex polymer components with high dimensional precision and repeatability. Acrylonitrile Butadiene Styrene (ABS) is a commonly used thermoplastic due to its excellent impact resistance, machinability, and aesthetic quality. However, defects such as shrinkage and warpage often compromise the final part quality. The incorporation of reinforcements like glass fiber and granite powder has shown promise in improving mechanical performance, giving rise to hybrid composites. To ensure high-

quality production, it is imperative to optimize the moulding parameters affecting both mechanical and dimensional outcomes. In this work, the Taguchi L₂₇ orthogonal array design was employed to study and optimize the process parameters for virgin and hybrid ABS composites. Key quality responses including shrinkage, warpage, and compressive strength were analyzed using signal-to-noise ratios and ANOVA to determine the most significant control factors. This study aims to enhance material performance and minimize processing defects through robust statistical optimization.

II. LITERATURE REVIEW

Previous research on ABS moulding has explored various aspects of its properties and applications, particularly in additive manufacturing and surface patterning. Volkhonsky's study highlights the physical and mechanical properties of ABS for aerodynamic models, demonstrating its suitability for wind tunnel testing under varying temperatures [1]. Shen et al. investigated the structural evolution of ABS during cycled fused deposition molding (FDM), revealing that repeated cycles can degrade its molecular structure and mechanical properties, leading to increased voids and reduced interfacial strength[2]. Melentiev and Lubineau proposed a novel viscous embossing technique for creating high-aspect-ratio textures on ABS, which improves replication accuracy and productivity compared to traditional methods[3]. Additionally, Mirasadi et al. examined the blending of ABS with PETG to enhance mechanical properties and shape memory effects, demonstrating the versatility of ABS in composite materials[4]. Finally, Sandhu et al. provided a comprehensive review of process parameter optimization in FDM, emphasizing the

importance of various printing parameters on the surface finish of ABS parts[5]. Collectively, these studies underscore the multifaceted applications and challenges associated with ABS moulding in modern manufacturing.

The integration of glass fiber and granite powder into acrylonitrile butadiene styrene (ABS) composites presents a promising approach to enhance mechanical properties while addressing waste management issues.[6] Studies indicate that the addition of short glass fibers significantly improves tensile strength and impact resistance, with a reported 57% increase in tensile strength at 30 wt% fiber content[7]. Conversely, while incorporating granite powder enhances stiffness and thermal conductivity, it can lead to a deterioration in tensile strength when exceeding 50% content[8]. The combination of these materials could leverage the benefits of both, potentially optimizing the mechanical performance of ABS composites for various applications, including structural uses in automotive and aerospace sectors[9]. Furthermore, the use of recycled granite powder aligns with sustainable practices, contributing to environmental friendliness in composite manufacturing[10].

The study of shrinkage, warpage, and compressive strength in ABS (Acrylonitrile Butadiene Styrene) materials reveals several critical insights into the optimization of these properties in both injection molding and 3D printing processes. Shrinkage in ABS is significantly influenced by parameters such as holding time and pressure during the injection molding process, with these factors being crucial for minimizing dimensional changes post-molding[11]. Additionally, the incorporation of materials like xanthan gum in ABS composites has been shown to effectively reduce after-shrinkage by altering the molecular structure, thereby enhancing the mechanical properties of the final product[12]. Warpage, a common issue in both injection molding and 3D printing, can be mitigated through strategic modifications. In 3D printing, altering infill patterns has proven effective in reducing warpage by addressing non-uniform shrinkage and thermal stresses, thus improving dimensional stability[13]. For injection molding, the use of advanced simulation techniques, such as those involving the pressure-volume-temperature relationship and solid mechanics analysis, allows for accurate predictions and reductions in warpage and shrinkage, aligning

theoretical models with experimental data[14]. Furthermore, blending recycled ABS with virgin ABS not only enhances tensile strength but also optimizes shrinkage, with packing pressure being a critical factor in achieving these improvements [15]. Collectively, these studies underscore the importance of precise control over processing parameters and material composition to enhance the performance and reliability of ABS products across various manufacturing techniques.

The Taguchi L27 orthogonal array is a robust experimental design tool utilized across various fields to optimize multiple process parameters efficiently. This array consists of 27 experimental runs, allowing for the evaluation of three levels of up to three factors simultaneously, making it particularly useful in manufacturing and material processing. For instance, in CNC turning of Aluminum 7075 alloy, the L27 array facilitated the optimization of parameters such as speed, feed, and cutting depth, leading to improved material removal rates and reduced surface roughness[16]. Similarly, in the context of fluid dynamics, the L27 array was employed to optimize heat and mass transfer rates in Prandtl fluid flow, demonstrating its versatility in addressing complex interactions among multiple variables[17]. Furthermore, the array has been effectively applied in environmental studies to assess the aggregation behavior of ZnO nanoparticles, highlighting its capability to analyze the influence of water chemistry parameters[18]. Additionally, in food technology, the L27 design was used to minimize solid not fat loss during paneer production, showcasing its practical applications in optimizing dairy processing parameters[19]. Overall, the L27 orthogonal array serves as a powerful framework for systematic experimentation and optimization across diverse domains.

The signal-to-noise ratio (SNR) is a critical component of the Taguchi method, serving as a key metric for optimizing design and process parameters across various applications. In the context of ZnO thin film CMOS SAW resonators, the SNR is utilized to enhance the electromechanical coupling coefficient, thereby improving device performance while minimizing design costs[20]. The Taguchi method, which incorporates the SNR, is widely recognized in quality control for its ability to improve product quality, reduce production costs,

and minimize output variation by effectively distinguishing between desired signals and unwanted noise[21]. In the design of a 22nm high-k/metal gate NMOS transistor, the Nominal-the-Best SNR is employed to optimize process parameters, demonstrating its utility in achieving target threshold voltage values[22]. Furthermore, the SNR is instrumental in assessing the robustness and uniformity of products, as it helps minimize the impact of undesirable and uncontrollable factors during the design phase, thus justifying investments in quality improvements[23]. In CNC milling operations, the SNR is applied to determine optimal machining parameters, such as spindle speed and feed rate, which are crucial for achieving high surface finish and material removal rates, thereby enhancing productivity. Overall, the SNR in the Taguchi method is indispensable for optimizing processes and ensuring high-quality outcomes across diverse manufacturing and engineering applications.

Past studies on ABS molding have explored its mechanical behavior, recyclability, and performance under different manufacturing processes. Research has shown that repeated FDM cycles degrade ABS properties, while techniques like viscous embossing improve surface replication. Blending with materials like PETG or glass fiber enhances mechanical strength, and using granite powder adds stiffness and sustainability. Shrinkage and warpage in ABS are influenced by molding parameters like pressure and cooling, and can be optimized with additives or simulation techniques.

III MATERIALS & METHODOLOGY

3.1 Compounding of Materials

The compounding of ABS granules, glass fiber, and granite powder was performed using a twin-screw co-rotating compounding machine, as shown in Figure 3.1 (Flytech Engineering, Model FUE-1C). This high-performance extruder is specifically designed for precise material blending. It operates at a maximum temperature of 400 °C, offers an adjustable output capacity ranging from 5 to 15 kg/h, and requires a minimum sample size of 200 g.



Fig: 3.1 Twin-screw co-rotating compounding machine

Table: 3.1 Mixing proportion of materials

Batch Code	Batch Name	ABS % of weight	Glass fiber % of weight	Granite powder % of weight
A	Pure ABS	100%	0%	0%
B	ABS+GF+GP	80%	10%	10%

3.2 Injection Moulding Process

The prepared hybrid PMC pellets were molded into standardized test specimens using a Milacron Nova 80 Servo injection molding machine, equipped with an 80-ton clamping force, as shown in Figure 3.2. Injection molding was selected for its capability to produce highly precise, repeatable, and defect-free specimens, which are essential for conducting accurate mechanical and thermal tests.



Fig: 3.2 Injection moulding Machine



Fig: 3.3 Virgin ABS & Hybrid ABS

IV. OPTIMIZATION OF PROCESS PARAMETERS

4.1 Selection of parameters range for virgin ABS (VABS) & Hybrid ABS (HABS)

Preliminary trials were conducted to identify optimal process parameter ranges for Virgin and

Hybrid ABS. Mold temperature was set between 50°C–80°C, and melt temperature between 230°C–290°C to ensure proper flow and avoid degradation. Injection pressure was optimized to 60–120 MPa, while packing pressure was maintained at 50–100 MPa to avoid defects and internal stresses. Packing time was chosen between 6–8 s, and cooling time between 12–32 s to balance quality and cycle time. These ranges, summarized in Table 4.1, were used in the Taguchi L₂₇ experimental design to optimize shrinkage, warpage, and compressive strength.

Table 4.1 Range of parameters for virgin ABS & Hybrid ABS

Parameters	Level-1	Level-2	Level-3	Unit
Mould Temperature(A)	50	65	80	°C
Melt Temperature(B)	230	260	290	°C
Injection Pressure (C)	60	90	120	MPa
Packing Time(D)	6	7	8	s
Packing Pressure (E)	50	75	100	MPa
Cooling Time(F)	12	22	32	s

The S/N ratios for these two cases are mathematically defined as follows:

Table 4.2. Orthogonal array for L₂₇ Taguchi design for shrinkage, warpage and compressive strength of VABS

L ₂₇ Run	A	B	C	D	E	F	Shrinkage (%)	Shrinkage S/N ratio(dB)	Warpage (mm)	Warpage S/N ratio(dB)	Compressive strength (N/mm ²)	Compressive strength S/N ratio(dB)
1	50	230	60	6	50	12	5.193	-14.3084	4.681	-13.4068	30.45	29.67
2	50	230	90	7	75	22	5.821	-15.3000	4.433	-12.9340	35	30.88
3	50	230	120	8	100	32	6.296	-15.9813	4.591	-13.2381	36.61	31.27
4	50	260	60	7	75	32	5.934	-15.4670	2.513	-8.0038	35.82	31.08
5	50	260	90	8	100	12	5.986	-15.5427	2.58	-8.2324	34	30.63
6	50	260	120	6	50	22	6.755	-16.5925	2.754	-8.7993	35.56	31.02
7	50	290	60	8	100	22	8.206	-18.2826	1.921	-5.6705	34.88	30.85
8	50	290	90	6	50	32	9.849	-19.8678	1.932	-5.7201	38.7	31.75
9	50	290	120	7	75	12	9.662	-19.7013	1.998	-6.0119	36.23	31.18
10	65	230	60	7	100	22	6.176	-15.8141	4.612	-13.2778	36.24	31.18
11	65	230	90	8	50	32	3.203	-10.1111	3.078	-9.7654	36.57	31.26
12	65	230	120	6	75	12	5.004	-13.9863	4.515	-13.0932	34.76	30.82
13	65	260	60	8	50	12	6.255	-15.9245	2.585	-8.2492	35.76	31.07
14	65	260	90	6	75	22	5.195	-14.3117	2.703	-8.6369	38.27	31.66

Lower is Better (LB) Formula

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right)$$

Higher is Better (HB) Formula:

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i} \right)$$

where:

- y_i = Observed response value
- n = Number of observations

4.2 Orthogonal array for L₂₇ Taguchi design for shrinkage, warpage & compressive strength of Virgin ABS

Table 4.2 & 4.3 presents the results of the Taguchi L₂₇ orthogonal array experiment conducted to analyze shrinkage, warpage, and compressive strength in virgin & hybrid ABS during injection molding. Six key process parameters were varied at three levels each. For all 27 experimental runs, the measured responses shrinkage, warpage, and compressive strength along with their corresponding signal-to-noise (S/N) ratios were recorded. The "smaller-the-better" criterion was applied for shrinkage and warpage, while the "larger-the-better" approach was used for evaluating compressive strength.

15	65	260	120	7	100	32	7.454	-17.4478	2.414	-7.6547	35.68	31.05
16	65	290	60	6	75	32	6.012	-15.5804	2.464	-7.8328	39.35	31.90
17	65	290	90	7	100	12	5.201	-14.3217	2.484	-7.9030	37.85	31.56
18	65	290	120	8	50	22	5.945	-15.4830	2.537	-8.0864	37.6	31.50
19	80	230	60	8	75	32	5.892	-15.4053	4.423	-12.9143	35.3	30.96
20	80	230	90	6	100	12	4.435	-12.9379	3.363	-10.5345	34.6	30.78
21	80	230	120	7	50	22	5.289	-14.4675	4.324	-12.7177	36.3	31.20
22	80	260	60	6	100	22	3.716	-11.4015	2.694	-8.6080	38.46	31.70
23	80	260	90	7	50	32	4.978	-13.9411	3.271	-10.2936	38.94	31.81
24	80	260	120	8	75	12	3.665	-11.2815	4.893	-13.7915	37.12	31.39
25	80	290	60	7	50	12	7.827	-17.8719	2.284	-7.1739	40.65	32.18
26	80	290	90	8	75	22	8.2	-18.2763	2.294	-7.2119	42.45	32.56
27	80	290	120	6	100	32	8.417	-18.5031	2.244	-7.0205	40.56	32.16

The Taguchi L₂₇ orthogonal array was used to analyze the effect of six key injection molding parameters—mold temperature (A), melt temperature (B), injection pressure (C), packing time (D), packing pressure (E), and cooling time (F)—each varied at three levels, on the performance of virgin ABS specimens.

Across 27 experimental runs:

Shrinkage ranged from 3.20% to 9.85%, with the lowest shrinkage observed at moderate mold and

melt temperatures combined with higher packing pressures and optimized packing/cooling times.

Warpage varied from 1.92 mm to 4.89 mm, showing minimal values when controlled cooling and packing pressures were applied, minimizing internal stress development.

Compressive strength values ranged from 30.45 to 42.45 N/mm², with the highest strength observed in runs using balanced injection and packing conditions, indicating proper material flow and solidification.

Table 4.3. Orthogonal array for L₂₇ Taguchi design for shrinkage, warpage and compressive strength of HABS

L ₂₇ Run	A	B	C	D	E	F	Shrinkage (%)	Shrinkage S/N ratio(dB)	Warpage (mm)	Warpage S/N ratio(dB)	Compressive strength (N/mm ²)	Compressive strength S/N ratio(dB)
1	50	230	60	6	50	12	5.373	-14.604	4.014	-12.0715	50.4	34.05
2	50	230	90	7	75	22	4.301	-12.671	3.982	-12.0020	53	34.49
3	50	230	120	8	100	32	4.182	-12.428	4.000	-12.0412	54	34.65
4	50	260	60	7	75	32	4.995	-13.971	1.789	-5.0522	54.4	34.71
5	50	260	90	8	100	12	4.826	-13.672	1.792	-5.0668	56.4	35.03
6	50	260	120	6	50	22	5.224	-14.360	2.003	-6.0336	53.8	34.62
7	50	290	60	8	100	22	8.348	-18.432	2.483	-7.8995	54.4	34.71
8	50	290	90	6	50	32	8.447	-18.534	2.537	-8.0864	56	34.96
9	50	290	120	7	75	12	9.482	-19.538	3.514	-10.9160	54.8	34.78
10	65	230	60	7	100	22	5.194	-14.310	2.991	-9.5163	54.7	34.76
11	65	230	90	8	50	32	2.32	-7.310	2.712	-8.6658	54.2	34.68
12	65	230	120	6	75	12	4.872	-13.754	3.582	-11.0825	52.7	34.44
13	65	260	60	8	50	12	5.172	-14.273	2.696	-8.6144	54.5	34.73
14	65	260	90	6	75	22	5.213	-14.342	2.798	-8.9370	56	34.96
15	65	260	120	7	100	32	6.371	-16.084	1.699	-4.6039	54.5	34.73

16	65	290	60	6	75	32	4.855	-13.724	2.706	-8.6466	57.8	35.24
17	65	290	90	7	100	12	4.018	-12.080	2.767	-8.8402	56.5	35.04
18	65	290	120	8	50	22	4.761	-13.554	4.902	-13.8075	56.8	35.09
19	80	230	60	8	75	32	4.709	-13.459	3.765	-11.5153	53.3	34.53
20	80	230	90	6	100	12	3.252	-10.243	3.897	-11.8146	53.6	34.58
21	80	230	120	7	50	22	4.107	-12.270	3.678	-11.3122	54	34.65
22	80	260	60	6	100	22	3.534	-10.965	2.593	-8.2761	57	35.12
23	80	260	90	7	50	32	4.797	-13.619	3.432	-10.7109	57.8	35.24
24	80	260	120	8	75	12	5.482	-14.779	2.462	-7.8258	57.4	35.18
25	80	290	60	7	50	12	5.646	-15.035	2.674	-8.5432	56.9	35.10
26	80	290	90	8	75	22	5.017	-14.009	2.458	-7.8116	58.7	35.37
27	80	290	120	6	100	32	7.017	-16.923	2.667	-8.5205	58.2	35.30

The experimental study using the Taguchi L_{27} orthogonal array investigates the influence of six process parameters on shrinkage, warpage, and compressive strength of hybrid ABS specimens manufactured by injection moulding. Shrinkage values range from 2.32% to 9.48%, with the lowest shrinkage observed in Run 11 and the highest in Run 9. Warpage varies between 1.699 mm and 4.902 mm, with minimal warpage recorded in Run 15 and maximum in Run 18. Compressive strength ranges from 50.4 N/mm² to 58.7 N/mm², peaking in Run 26. The results suggest that melt temperature, cooling time, and packing pressure significantly influence the quality characteristics. Runs with moderate shrinkage and warpage while maintaining high compressive strength indicate optimal parameter combinations, emphasizing the importance of a balanced setting for improved mechanical performance.

Table: 4.3: Response Table for Signal to Noise Ratios for shrinkage of Virgin ABS

Level	A	B	C	D	E	F
1	-16.78	-14.26	-14.18	-16.44	-15.56	-15.57
2	-14.78	-14.66	-15.80	-15.09	-14.96	-15.81
3	-14.90	-17.54	-16.48	-14.93	-15.94	-15.08
Delta	2.01	3.29	2.31	1.50	0.98	0.73
Rank	3	1	2	4	5	6

Table: 4.4: Response Table for Signal to Noise Ratios for warpage of Virgin ABS

Level	A	B	C	D	E	F
1	-	-	-	-	-	-
	9.113	-12.431	10.677	-9.503	-9.460	9.328
2	-	-	-	-	-	-
	9.389	-9.141	-9.175	-9.447	-9.026	9.975

3	-	-	-	-	-	-
	10.03	-6.959	-8.679	-9.581	-10.046	9.228
Delta	0.917	5.472	1.998	0.134	1.020	0.747
Rank	4	1	2	6	3	5

Table: 4.5: Response Table for Signal to Noise Ratios for compressive strength of Virgin ABS

Level	A	B	C	D	E	F
1	30.93	30.89	31.30	31.39	31.18	31.13
2	31.33	31.27	31.43	31.18	31.43	31.35
3	31.64	31.74	31.17	31.33	31.29	31.42
Delta	0.71	0.85	0.27	0.21	0.26	0.30
Rank	2	1	4	6	5	3

Table: 4.6: Response Table for Signal to Noise Ratios for shrinkage of Hybrid ABS

Level	A	B	C	D	E	F
1	-	-12.34	-13.16	-14.49	-14.31	-14.25
	15.36					
2	-	-14.01	-13.70	-13.04	-12.94	-14.57
	13.27					
3	-	-15.76	-15.24	-14.58	-14.85	-13.28
	13.48					
Delta	2.09	3.42	2.08	1.55	1.91	1.29
Rank	2	1	3	5	4	6

Table: 4.7: Response Table for Signal to Noise Ratios for warpage of Hybrid ABS

Level	A	B	C	D	E	F
1	-	-11.114	-10.469	-	-8.904	-
	8.797			9.238		9.428
2	-	-7.236	-7.810	-	-9.104	-
	9.190			9.121		8.843
3	-	-9.230	-9.300	-	-9.571	-
	9.592			9.220		9.308

Delta	0.796	3.878	2.659	0.117	0.668	0.585
Rank	3	1	2	6	4	5

Table: 4.8: Response Table for Signal to Noise Ratios for compressive strength of Hybrid ABS

Level	A	B	C	D	E	F
1	34.67	34.54	34.90	34.82	34.77	34.77
2	34.85	34.92	34.89	34.83	34.93	34.93
3	35.01	35.07	34.74	34.87	34.82	34.83
Delta	0.34	0.53	0.16	0.05	0.16	0.16
Rank	2	1	3	6	5	4

For Virgin ABS, the most influential parameter on shrinkage is factor B (Melt Temperature), followed by C (Packing Pressure) and A (Injection Pressure). For warpage, again B (Melt Temperature) ranks highest in influence, followed by C (Packing Pressure). For compressive strength, B (Melt Temperature) and A (Injection Pressure) are most significant.

For Hybrid ABS, B (Melt Temperature) is the dominant factor for both shrinkage and warpage, with C (Packing Pressure) and A (Injection Pressure) also showing notable effects. In terms of compressive strength, B and A again lead, with relatively small deltas, indicating more consistent strength across levels. Overall, melt temperature (B) consistently emerges as the most influential factor across all responses.

V. ANALYSIS OF VARIANCE (ANOVA)

Table: 5.1 ANOVA for Shrinkage of VABS

Source	DF	Adj SS	Adj MS	F-value	p-value	Effect
Mould temperature	2	16.69	8.345	19.5948	0	Significant
Melt Temperature	2	91.34	45.67	107.257	0	Significant
Injection Pressure	2	18.78	9.39	22.0526	0	Significant
Packing Time	2	1.091	0.5455	1.28112	0.391	Not significant
Packing Pressure	2	1.06	0.53	1.24472	0.341	Not significant
Cooling Time	2	0.362	0.181	0.42508	0.557	Not significant
Mould temperature × Melt Temperature	4	40.838	10.2095	23.9772	0	Significant
Melt Temperature × Injection Pressure	4	16.214	4.0535	9.51973	0	Significant
Error	33	14.054	0.4258788			
R ²		90.21%				
Adjusted R ²		87.45%				

Table: 5.2 ANOVA for warpage of VABS

Source	DF	Adj SS	Adj MS	F-value	p-value	Effect
Mould temperature	2	3.68	1.84	10.5626	0.007	Significant
Melt Temperature	2	73.092	36.546	209.793	0	Significant
Injection Pressure	2	4.398	2.199	12.6234	0	Significant
Packing Time	2	0.349	0.1745	1.00172	0.483	Not significant
Packing Pressure	2	1.832	0.916	5.25832	0.004	Significant
Cooling Time	2	1.722	0.861	4.94259	0.013	Significant
Mould temperature × Melt Temperature	4	9.824	2.456	14.0987	0	Significant
Melt Temperature × Injection Pressure	4	8.724	2.181	12.5201	0	Significant
Error	33	5.751	0.1742727			
R ²		92.17%				
Adjusted R ²		88.56%				

Table: 5.3 ANOVA for compressive strength of VABS

Source	DF	Adj SS	Adj MS	F-value	p-value	Effect
Mould temperature	2	56.75	28.375	350.309	0	Significant
Melt Temperature	2	90.979	45.4895	112.61	0	Significant
Injection Pressure	2	21.41	10.705	50.44	0	Significant
Packing Time	2	1.471	0.7355	9.02	0.072	Not significant
Packing Pressure	2	11.4	5.7	20.96	0	Significant
Cooling Time	2	36.62	18.31	25.84	0	Significant
Mould temperature × Melt Temperature	4	18.5	4.625	49.16	0	Significant
Melt Temperature × Injection Pressure	4	8.67	2.1675	27.45	0	Significant
Mould temperature × Injection Pressure	4	6.67	1.6675	16.45	0	Significant
Error	29	2.364	0.081517			
R ²		95.16%				
Adjusted R ²		91.27%				

Table: 5.4 ANOVA for Shrinkage of HABS

Source	DF	Adj SS	Adj MS	F-value	p-value	Effect
Mould Temperature	2	18.679	9.3394	21.93	0.000	Significant
Melt Temperature	2	75.73	37.8649	88.91	0.000	Significant
Injection Pressure	2	12.574	6.287	14.76	0.000	Significant
Packing Time	2	1.091	0.5454	1.28	0.291	Not significant
Packing Pressure	2	1.09	0.5451	1.28	0.291	Not significant
Cooling Time	2	0.362	0.1809	0.42	0.657	Not significant
Mould temperature × Melt Temperature	4	40.838	10.2094	23.97	0.000	Significant
Melt Temperature × Injection Pressure	4	16.214	4.0535	9.52	0.000	Significant
Error	33	14.054	0.4259			
R ²		94.42%				
Adjusted R ²		91.04%				

Table: 5.5 ANOVA for warpage of HABS

Source	DF	Adj SS	Adj MS	F-value	p-value	Effect
Mould temperature	2	2.039	1.0196	5.85	0.007	Significant
Melt Temperature	2	68.092	34.0459	195.36	0.000	Significant
Injection Pressure	2	4.398	2.199	12.62	0.000	Significant
Packing Time	2	0.259	0.1296	0.74	0.483	Non-Significant
Packing Pressure	2	2.332	1.166	6.69	0.004	Significant
Cooling Time	2	1.722	0.861	4.94	0.013	Significant
Mould temperature × Melt Temperature	4	9.824	2.4559	14.09	0.000	Significant
Melt Temperature × Injection Pressure	4	8.724	2.1809	12.51	0.000	Significant
Error	33	5.751	0.1743			
R ²		93.35%				
Adjusted R ²		91.56%				

Table: 5.6 ANOVA for compressive strength of HABS

Source	DF	Adj SS	Adj MS	F-value	p-value	Effect
Mould temperature	2	16.838	8.41911	103.26	0.00	Significant
Melt Temperature	2	18.364	9.18178	112.61	0.00	Significant
Injection Pressure	2	8.225	4.11244	50.44	0.00	Significant
Packing Time	2	1.471	0.73556	9.02	0.072	Non-Significant
Packing Pressure	2	3.418	1.70889	20.96	0.00	Significant
Cooling Time	2	4.213	2.10667	25.84	0.00	Significant
Mould temperature × Melt Temperature	4	16.031	4.00778	49.16	0.00	Significant
Melt Temperature × Injection Pressure	4	8.951	2.23778	27.45	0.00	Significant
Mould temperature × Injection Pressure	4	5.364	1.34111	16.45	0.00	Significant
Error	29	2.364	0.08153			
R ²		97.26%				
Adjusted R ²		95.23%				

The ANOVA analysis across all responses for Virgin ABS (VABS) and Hybrid ABS (HABS) confirms that Melt Temperature is the most influential process parameter, consistently showing a highly significant effect on shrinkage, warpage, and compressive strength. Mould Temperature and Injection Pressure also play major roles in affecting these responses. In contrast, Packing Time is not statistically significant in most cases. Significant

interaction effects, particularly between Mould Temperature \times Melt Temperature and Melt Temperature \times Injection Pressure, further emphasize the complex interplay between parameters. All models demonstrate strong predictive capability, with R^2 values above 90%, confirming the reliability of the experimental data and the Taguchi-based approach.

VI. RESULTS & DISCUSSION



Fig: 6.1 Main effects plot for Signal to Nois ratios for shrinkage of Virgin ABS

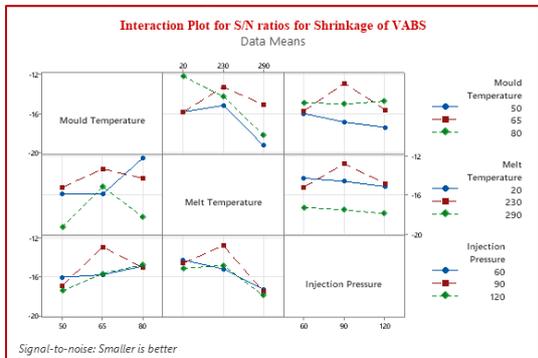


Fig: 6.2 Parameters Interaction plots for shrinkage of VABS

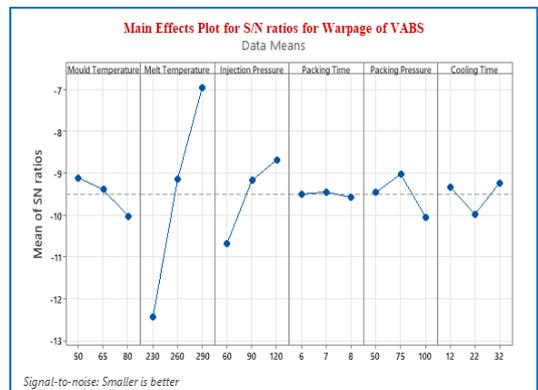


Fig: 6.3 Main effects plots for S/N ratios for warpage of VABS

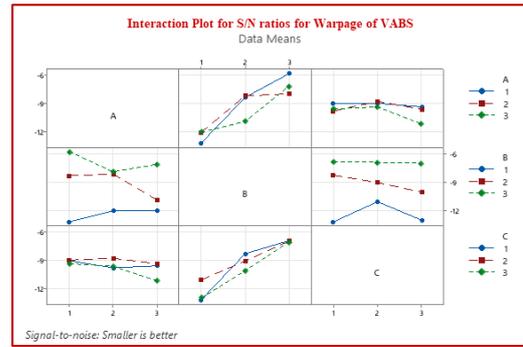


Fig:6.4 Parameters Interaction plots for warpage of VABS

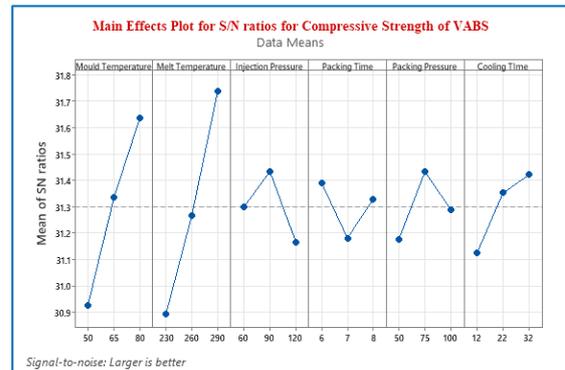


Fig:6.5 Main effects plots for S/N ratios for compressive strength of VABS

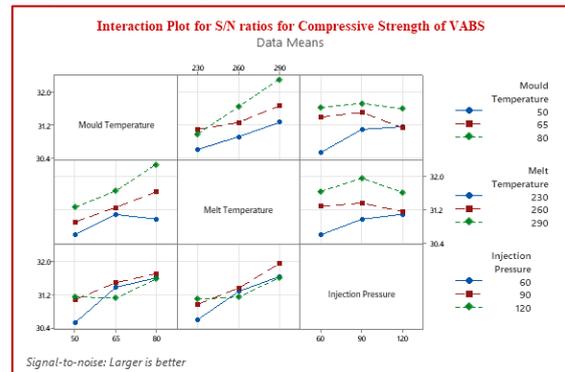


Fig:6.6 Parameters Interaction plots for compressive strength of VABS

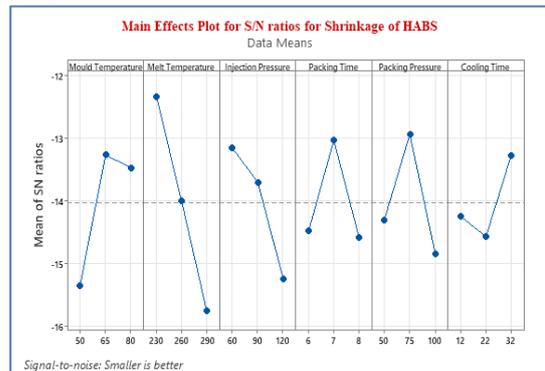


Fig:6.7 Main effects plots for S/N ratios for shrinkage of HABS

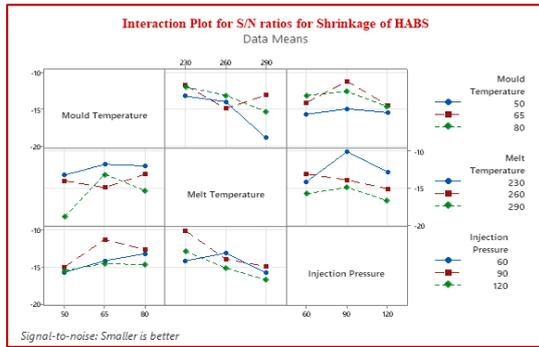


Fig:6.8 Parameters Interaction plots for shrinkage of HABS

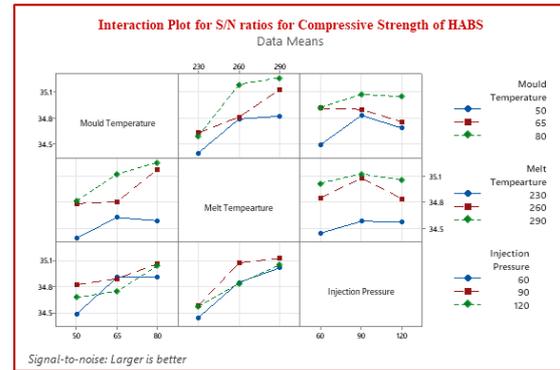


Fig:6.12 Parameters Interaction plots for compressive strength of HABS

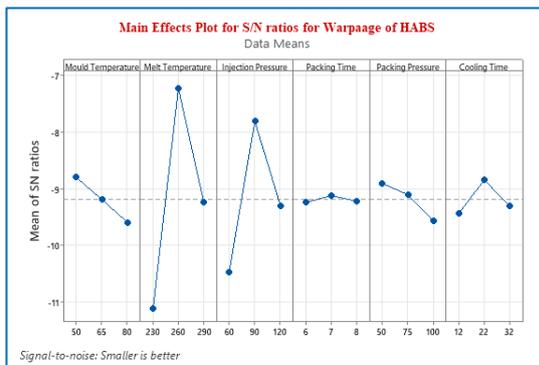


Fig: 6.9 Main effects plots for S/N ratios for warpage of HABS

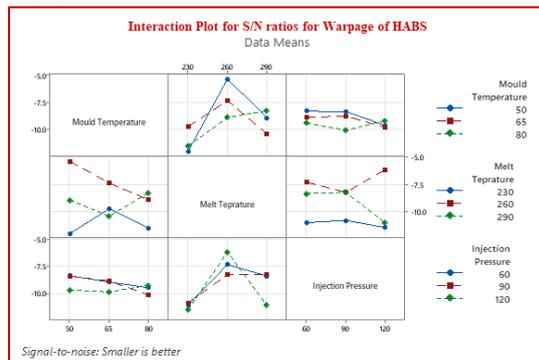


Fig:6.10 Parameters Interaction plots for warpage of HABS

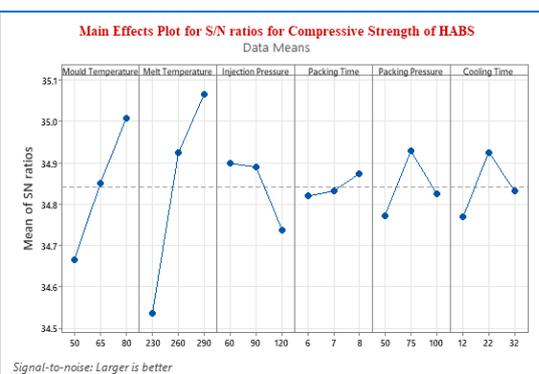


Fig:6.11 Main effects plots for S/N ratios for warpage of HABS

6.1 Main effects plots for signal-to-noise (S/N) ratios & Interaction plots

The main effects plots for signal-to-noise (S/N) ratios illustrate the influence of individual injection molding parameters on shrinkage, warpage, and compressive strength of Virgin ABS (VABS) and Hybrid ABS (HABS). For VABS, melt temperature and injection pressure are the most influential parameters for shrinkage, with shrinkage worsening significantly at a melt temperature of 290°C and showing optimal results around 60 bar injection pressure. Parameters like packing time, packing pressure, and cooling time show minimal impact. In terms of warpage, melt temperature again plays the dominant role, with improved performance at 290°C, followed by injection pressure, which shows optimal results around 120 bar. Mould temperature has a moderate influence, while packing time shows the least effect. For compressive strength of VABS, mould temperature and melt temperature are the key contributors, with higher values of both parameters (up to 80°C and 290°C respectively) resulting in improved strength. Injection pressure and other parameters show modest effects, with minor improvements at specific levels.

Similarly, for HABS, shrinkage is most affected by melt temperature and injection pressure. Shrinkage increases at higher melt temperatures, while moderate injection pressure around 60 bar reduces it. Cooling time and packing pressure also show some positive influence, suggesting longer cooling (32s) and a packing pressure of 75 bar help reduce shrinkage. Warpage in HABS is primarily influenced by melt temperature, with 260°C offering the best performance, and by injection pressure, where 90 bar proves optimal. Other parameters, including mould temperature and packing variables, show little variation. For compressive strength,

mould temperature, melt temperature, and injection pressure are again the most significant, with the best results at 80°C mould temperature, 290°C melt temperature, and 60 bar injection pressure. Packing time, packing pressure, and cooling time have minimal impact. Overall, melt temperature emerges as the most critical parameter across all responses, followed by injection pressure and mould temperature, while the remaining parameters,

although less impactful individually, may still contribute when fine-tuned in combination.

6.2 Prediction of S/N ratio for Virgin ABS & Hybrid ABS

For Taguchi, predicted S/N ratio is given by:

$$\text{Predicted } \eta \text{ (S/N)} = \eta_{\text{mean}} + (\eta_{\text{optA}} - \eta_{\text{mean}}) + (\eta_{\text{optB}} - \eta_{\text{mean}}) + \dots + (\eta_{\text{optF}} - \eta_{\text{mean}})$$

Where:

η_{mean} = overall mean S/N ratio

η_{optX} = S/N ratio for the optimal level of factor X

Table:6.1 Summary of predicted S/N ratio for Virgin & Hybrid ABS

Response	Optimal combination	Predicted S/N ratio
Shrinkage-VABS	A ₂ B ₁ C ₁ D ₃ E ₂ F ₁	-11.252
Warpage-VABS	A ₂ B ₂ C ₂ D ₂ E ₂ F ₃	-7.853
Compressive strength-VABS	A ₃ B ₃ C ₂ D ₁ E ₂ F ₃	32.5524
Shrinkage-HABS	A ₂ B ₁ C ₁ D ₃ E ₂ F ₁	-10.365
Warpage-HABS	A ₂ B ₂ C ₂ D ₂ E ₂ F ₂	-5.3385
Compressive strength-HABS	A ₃ B ₃ C ₂ D ₁ E ₂ F ₂	35.442

6.36 Confirmation Experiment

Table: 6.22 Confirmation experiment test results of virgin & hybrid ABS

Response	Optimal combination	Predicted S/N ratio	Confirmation experimental S/N ratio	Error
Shrinkage-VABS	A ₂ B ₁ C ₁ D ₃ E ₂ F ₁	-11.252	-11.876	5.55
Warpage-VABS	A ₂ B ₂ C ₂ D ₂ E ₂ F ₃	-7.853	-8.343	6.24
Compressive strength-VABS	A ₃ B ₃ C ₂ D ₁ E ₂ F ₃	32.5524	31.450	3.39
Shrinkage-HABS	A ₂ B ₁ C ₁ D ₃ E ₂ F ₁	-10.365	-10.955	5.69
Warpage-HABS	A ₂ B ₂ C ₂ D ₂ E ₂ F ₂	-5.3385	-5.689	6.56
Compressive strength-HABS	A ₃ B ₃ C ₂ D ₁ E ₂ F ₂	35.442	34.170	3.59

The confirmation experiments for both Virgin ABS (VABS) and Hybrid ABS (HABS) validate the optimal parameter combinations derived from the Taguchi method. For shrinkage in both VABS and HABS, the experimental S/N ratios (-11.876 and -10.955, respectively) closely align with the predicted values (-11.252 and -10.365), confirming the reliability of the optimization. Similarly, warpage results for VABS and HABS show strong agreement between predicted and experimental S/N ratios (VABS: -7.853 predicted vs -8.343 actual; HABS: -5.3385 predicted vs -5.689 actual), reaffirming the significance of melt temperature and injection pressure. For compressive strength, both materials show slightly lower experimental S/N ratios than predicted (VABS: 31.450 vs 32.5524; HABS: 34.170 vs 35.442), yet the results still support the effectiveness of the identified optimal settings. Overall, the confirmation tests demonstrate that the selected processing conditions significantly enhance the performance characteristics of both VABS and HABS materials.

VII. CONCLUSION

The experimental results for Virgin ABS (VABS) and Hybrid ABS (HABS) composites confirm the effectiveness of the Taguchi method in optimizing injection molding parameters for improved performance. Among all the process variables, Melt Temperature, Injection Pressure, and Mould Temperature consistently emerged as the most influential factors across all responses shrinkage, warpage, and compressive strength. Interaction effects, particularly between Melt Temperature × Injection Pressure and Mould Temperature × Melt Temperature, were also significant, highlighting the complex interplay of parameters in determining the final material properties. The high R² and adjusted R² values across ANOVA analyses further validate the statistical strength and predictive accuracy of the models. Additionally, the main effects plots for S/N ratios emphasized that optimal settings not only vary by response but also confirm that a balance of thermal and pressure parameters is crucial. The confirmation experiments yielded S/N ratios close to the predicted values, reinforcing the robustness of the optimization approach. Overall, the study provides strong evidence that careful tuning of key injection molding parameters can significantly reduce shrinkage and warpage while enhancing the compressive strength of both VABS and HABS composites.

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