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FABRICATION AND OPTIMIZATION OF NATURAL FIBER COMPOSITES USING COMPRESSION MOLDING BY TAGUCHI GREY RELATIONAL METHODS

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ABSTRACT
This study investigates the utilization of Taguchi Design of Experiments paired with Autodesk Mold flow analysis to ascertain the optimal processing conditions for creating natural Composite structures made of fibers and polymers. The composite matrix evaluated consists of recycled plastic reinforced by 10% wood fiber. Optimization efforts focused on four pivotal variables: compression time, mold temperature, melt temperature, and applied pressure. By leveraging an L9 orthogonal array, the process was evaluated in Mold flow through distinct parameter combinations. Simulation-derived war page data were transformed into signal-to-noise (S/N) ratios, and the optimal setting for each factor was isolated using the smaller-the-better performance metric. Analytical results pointed to a specific set of optimal conditions: a mold temperature of 60 °C, compression time of 40 s, melt temperature of 210 °C, and pressure of 600 kn. A confirmatory experiment was conducted to verify the efficacy of these settings. Furthermore, Analysis of Variance (ANOVA) revealed that melt temperature was the most influential factor regarding war page, followed in importance by mold temperature, compression, pressure."

Keywords:
Compression molding; design of experiment; Mold flow; optimization; process parameters

1. INTRODUCTION

Natural Fiber–Polymer Composites (NFPC) have become an increasingly important material for manufacturing and building. These materials are not longer limited to basic housing applications; they are rapidly becoming a staple in high- Automotive and other technological industries
, electronics, and aerospace [1]. This growth
is mostly driven by the needfor lightweight yet strong components [2, 3]., NFPCs are lighter than many alternatives while maintaining a robust mechanicaland dielectric capabilities. They also bring benefits regarding cost, specific strength, Additionally, strict The transition to such sustainable materials is being driven by laws and environmental concerns.Consequently, incorporatingNFPCs helps manufacturers save money through low-cost inputs and improves their brand reputation in a competitive market the polymer matrix within NFPCs is typically divided into thermoplastics, such as polypropylene (PP), acrylonitrile-butadiene-styrene (ABS), and polyamide (PA), or Thermo setting materials, such as polyester and epoxy. Although virgin materials are frequently utilized,there is rising interest in the potential of recycled polymers among scientists and producers alike [6,7]. These composites are made using a range of production techniques. comprising methods such as resin transfer molding, which includes extrusion, molding by compression, and molding with injections
[2,8,9]. Compression molding is extensively utilized to create NFPCs due to its substantial productivity, The cost-effectiveness of compression molding synergizes with the low material costs of NFPCs, which can be lowered even further through the utilization of recycled plastics. Conversely, injection molding is likewise a high-output method. but demands sophisticated and pricey tooling infrastructure [10]. This technique is typically optimal for processing pure polymers; however, with NFPCs, there is a potential for fiber obstruction at the gate or runner due to the narrow flow paths [9]. Alternatively, compression molding entails depositing the composite mixture between the upper and lower mold sections, where
The application of temperature and pressure shapes the component.

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[8,10,11]." that processing NFPCs through compression molding relies heavily on three key factors: temperature, time, and pressure [12,13]. Improving these for use in factories settings is necessary to ensure peak Effectiveness of the production line while fulfilling Quality specifications and cost-saving goals. A primary objective during optimization is the reduction of processing time, which has a direct positive impact on output rates and manufacturing costs. However, engineers must balance this by ensuring that shortened cycle times do not lead to potential defects in the final part [14]."A handful of studies have especially
Addressed the optimization of manufacturing parameters for NFPCs during compression molding [11,15–18]. Currently, the Taguchi primary tool used to optimize parameters for both compression [11,17] and injection molding [19,20]. Selmat et al. [11] established the best compression molding conditions for pineapple leaf fiber–PP composites to achieve peak tensile strength. They reported that 30 kg/cm² of pressure, 175 °C, 6 minutes of preheating, and 4 minutes of compression time were the ideal settings. Similarly, optimized temperature, time, mixing speed, and fiber size for kenaf-polyurethane composites, finding that 180 °C, 50 rpm, 13 minutes, and 125–300 µm fibers yielded the highest tensile strength. Ibrahim et al. [20] also applied the Taguchi technique, using orthogonal arrays (OA) and signal-to-noise (S/N) ratios to isolate the best processing combinations."
this study implements a hybrid approach using Taguchi DOE and Autodesk Mold flow® simulation to optimize the compression molding of NFPCs. The goal is to reduce war page and meet specific quality standards. The DOE utilizes the S/N ratio of the wa page values as its main objective function. Furthermore, ANOVA was conducted to determine how significantly each processing parameter influences the final war page. Combining S/N ratio results with ANOVA allowed for the determination of the optimal set of process variables."

2. MATERIALS AND METHODS

Material Composition and Properties

Waste polymers recovered from automotive and heavy vehicle parts served as the base material for this study. The composition was predominantly ABS (80.77%), with the remainder consisting of styrene-based blends like ABS–PS, ABS–SAN, ABS–ASA, ABS–AES, and ABS–PMMA. Following granulation of the plastic waste, we conducted laboratory tests to establish its material properties. Measured values for melt density, solid density, mechanical performance, and melt flow rate were then uploaded to the Mold flow Insight database. For thermal properties, a generic ABS material from the existing Mold flow library was used as a reference. The comprehensive polymer data applied in the simulation are detailed in Table 1."

Table 1. Characterization of the recycled ABS-blend matrix.

Parameter Description	Unit	Modified Value
Melt state density	kg/m^3	952
Solid state density	kg/m^3	1045
Melt Flow Index (MFI)	g/10 min	31.25
Glass transition temperature (T_g)	°C	102
Modulus of Elasticity (E)	MPa	1815
Poisson's ratio (v)	—	0.38
Modulus of Rigidity (G)	MPa	985.4
Specific heat capacity (C_p)	$J/kg \cdot °C$	2415
Thermal conductivity (k)	$W/m \cdot °C$	0.175

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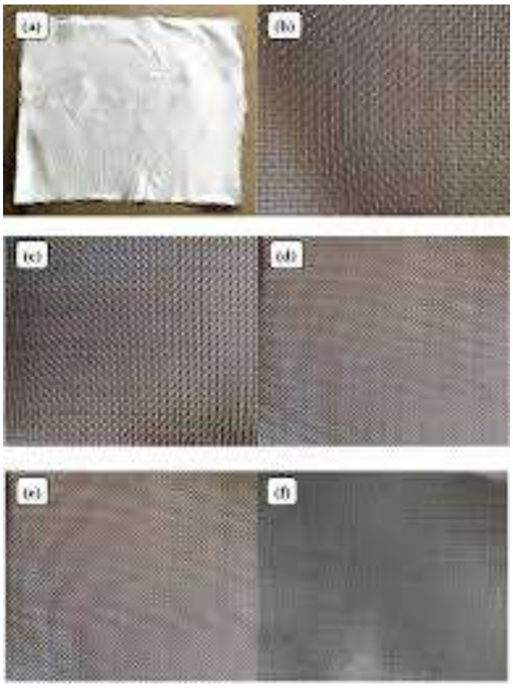
Coniferous wood properties were pre-loaded in the database. For better performance, the blend was modified with exact elastomer for improved flow and STRUKTOL TPW 113 to ensure easy part removal from the tooling. The supplier-provided data for these additives was added to the Mold flow environment. The final proportions of the composite ingredients are summarized in

Table 2 below."

Constituent	***Classification***	***Mass Fraction (%)***
Recycled ABS Blend	***Polymer Matrix***	***81.5***
Coniferous Wood Fiber	***Reinforcement***	***10.0***
STRUKTOL® TPW 113	***Lubricant***	***2.5***
Exact Elastomer	***Impact Modifier***	***6.0***

"The optimization framework in this study was applied to an automotive battery cover, a component designed in-house to validate the use of recycled NFPCs as a replacement for virgin plastic parts. After the primary design was finalized in Solid Works 2017, the file was transitioned into Autodesk Mold flow Insight 2021 for the simulation phase. The component spans 340 mm in length and 170 mm in width, featuring a variable thickness profile of 2.5 to 4 mm. To account for these geometric intricacies, we opted for 3D meshing one of the three available types in Mold flow to maintain high simulation accuracy. While this selection required more intensive computational resources, it produced a robust mesh of 1,179,779 elements for the final war page analysis.



Design of Experiments via Taguchi Method

The Taguchi approach is extensively adopted in the engineering field to fine-tune performance characteristics through the optimization of design parameters [27]. It is structured into three essential tiers: system, parameter,

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International Journal of Engineering Technology Research & Management (IJETRM)
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and tolerance design. This DOE technique provides a mathematical foundation for multi-factor testing, To conduct the DOE in this research, we selected melt temperature, mold temperature, compression time, and pressure as our independent factors, as summarized in Table 3.

Table 3. Level of factors affecting the compression molding process.

Symbol	Control Factor	Unit	Level 1	Level 2	Level 3
A	Mold Temperature	°C	55	65	75
B	Compression Duration	s	35	45	55
C	Melt Temperature	°C	205	215	225
D	Applied Pressure	kN	450	550	650

By employing a strategically designed OA, Taguchi DOE curtails the necessary experimental iterations needed to explore all parameter combinations [27, 29]. This matrix is a vital tool for the orderly arrangement of test runs and the rigorous interpretation of findings. To achieve this, an $L_9 (3^4)$ orthogonal array was selected for this investigation, which manages four factors at three levels each, as detailed in the experimental matrix in Table 4."

Table 4. The LP orthogonal array

Exp. No.	Factor A: Mold Temp (°C)	Factor B: Comp. Time (s)	Factor C: Melt Temp (°C)	Factor D: Pressure (kN)
1	55	35	205	450
2	55	45	215	550
3	55	55	225	650
4	65	35	215	650
5	65	45	225	450
6	65	55	205	550
7	75	35	225	550
8	75	45	205	650
9	75	55	215	450

3. RESULTS

3.1. Taguchi DOE

The war page data and quality assessments resulting from the Taguchi iterations are detailed in Table 5. Mold flow classifies a part as 'good quality' if the chosen processing parameters yield a product that fulfills all standard expectations for both aesthetics and material integrity. A 'bad quality' rating, however, is assigned

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when the part suffers from a short shot. Defined as the partial filling of the mold cavity, a short shot prevents the material from reaching the furthest extremities of the tool, thereby producing an unfinished part."

Table 5. Simulation Outcomes: Product Quality and War page Performance

Trial No.	A	B	C	D	Part Quality	Warpage (mm)
1	1	1	1	1	**Unsatisfactory** (Short Shot)	1.512
2	1	2	2	2	Satisfactory	1.488
3	1	3	3	3	Satisfactory	1.518
4	2	1	2	3	Satisfactory	1.505
5	2	2	3	1	Satisfactory	1.534
6	2	3	1	2	Satisfactory	1.522
7	3	1	3	2	Satisfactory	1.569
8	3	2	1	3	Satisfactory	1.498
9	3	3	2	1	Satisfactory	1.529

3.2 ANOVA

In this section, Analysis of Variance (ANOVA) was implemented to quantify the relative impact of each processing variable on the resulting warpage. The statistical breakdown, comprising the sum of squares (SS), degrees of freedom (DOF), variance (V), F-ratio, and the percentage contribution ($P\%$), is detailed in Table 9.Interpretation of these results relies heavily on the F-ratio and $P\%$ values. A high F-ratio corresponds to a lower p-value, confirming the statistical significance of the factor. Simultaneously, the $P\%$ value highlights the magnitude of a parameter's influence. As shown in Table 9, melt temperature (C) emerged as the dominant factor, accounting for 48.12% of the total effect on warpage. Other variables followed in descending order of significance: mold temperature (A at 24.73%), compression duration (B at 16.33%), and molding pressure (D at 10.82%).These findings align with the research conducted by Hussain et al. [31], who utilized Taguchi methods and simulation tools to optimize injection molding parameters. Their study similarly identified melt temperature as the primary driver of war page variations.

Table 6. Analysis of Variance (ANOVA) for War page Minimization

Parameter	DOF	SS	V (Variance)	F-Ratio	P% (Contribution)
A: Mold Temp	2	0.00114	0.000570	1.054	25.12
B: Comp. Time	2	0.00068	0.000340	0.628	14.98
C: Melt Temp	2	0.00223	0.001115	2.061	49.11
D: Pressure	2	0.00049	0.000245	0.453	10.79

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Parameter	DOF	SS	V (Variance)	F-Ratio	P% (Contribution)
Total	8	0.00454	—	—	100.00

CONCLUSION

"The objective of this work was to refine the manufacturing parameters for an NFPC component using Mold flow simulation and Taguchi DOE principles. Utilizing an L_9 orthogonal array, ANOVA to pinpoint the ideal combination of process factors. A confirmation test verified these findings, yielding the final war page and fill time metrics. Statistical analysis via ANOVA revealed that melt temperature exerted the most significant influence on part war page with a **49.11%** contribution, while mold temperature, compression duration, and pressure accounted for the remaining **25.12%**, **14.98%**, and **10.79 %**, respectively.

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