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An integrated approach of quality for polymer composite manufacturing validated and optimized through Taguchi method

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KEYWORDS

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Abstract. Quality problems in the polymer composite products are mainly attributed to design flaws, material inconsistencies, defects in manufacturing process, unqualified manpower, use of primitive technology, and defective machines. The purpose of this research is to develop a generic framework of quality for polymer composite manufacturing, which is validated and optimized through determining flexure properties by Taguchi method. To test the proposed framework, 27 polymer composite laminates were produced according to Taguchi L_{27} orthogonal array by varying thirteen key process parameters including laminates' thickness, weight, fiber pattern, matrix, core type, resin and hardener mixing time, viscosity, layup pattern, tooling, cure, temperature, labour and process techniques. Flexure strength was defined as quality characteristic, and accordingly, effects of the selected parameters on flexural properties were studied through three-point bending test. Results of the study reveal that fiber pattern, cure, tooling type, and layup pattern are the most significant variables influencing flexure stress, whereas fiber pattern, matrix, resin hardening mixing time, and process techniques have significant effect on flexure strain. The optimized levels of each control parameter for flexure stress and strain were obtained, and results were validated through predictive analysis. Findings of this study and the proposed framework are useful for polymer composite application in aviation, mechanical, sports, automobile, and civil industries.

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1. Introduction

Material properties, such as mechanical, chemical, and physical ones, are embedded during the polymer composite manufacturing process [1]. Small variation in raw material, processing, tooling, laying or autoclave

loading could result in a large amount of variation in cured composite parts [2]. For acceptable products, all key manufacturing control parameters, such as environment control, raw material control, production tolerances, dimensional tolerance control, thermal control, etc., have to conform to pre-established production criteria. Certain tests are needed to control mechanical, chemical, and physical properties along with development and documentation of process conditions [3]. It is very difficult to detect material defects through quality control tests such as incoming material inspections and acceptance procedures. John and Yeow [4] put empha-

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sis on the process and end of product properties. They classified 66 prepreg vital characteristics and process parameters that have major effect on properties of structure. Out of those, 26 characteristics significantly affected the structural performance. According to Galappaththil et al., manufacturing dichotomies and inconsistencies of resin infusion process could be reduced by controlling key control process parameters [5]. Potter et al. reviewed the causes of inconsistencies in aviation composite parts and recommended robust design in manufacturing process [6]. They identified 130 defect types, 60 sources of variability in material, molding and post-molding process in autoclave and resin transfer molding techniques. Quality problem in the composite products is mainly attributed to design flaws, material inconsistencies, defects in manufacturing process, untrained/unqualified manpower, and defective machines. Common problems faced by the composite industries include imperfections in parts, excessive labour involvement, complexity in machining operations, intricacies in manufacturing, assembly and bonding, which resulted in quality, ergonomics, and serviceability problems. The problems and difficulties encountered during manufacturing parts are ultimately responsible for higher rejection rate and increased production cost [7,8].

2. Description

Although researchers have done an appreciable amount of work on quality control, quality assurance, and various sources of variability in composite manufacturing processes, the existing literature lacks the integrated quality framework, which could be applicable to various polymer composite production processes and could facilitate manufacturers to provide key variables specific to different stages of manufacturing. This research is aimed to integrate the variables involved in design, material, key process control parameters, and testing of polymer composite manufacturing into one generic framework, and accordingly, their effects on the product quality are studied. Then, the developed framework is tested and validated through determination of flexure properties by using design of experiment technique. The paper is organized in the following chronological order: Section 2.1 describes the problem formulation; Section 2.2 represents the proposed quality framework; Section 3 elucidates the research methodology and data collection technique; Section 4 represents results and discussion; Section 5 focuses on conclusion and area of future research.

2.1. Problem formulation

Problem for this research has been formulated in the following way:

- a. Integrated quality framework is developed for polymer composite manufacturing;
- b. Key control parameters affecting product quality are selected;
- c. Polymer composite laminates are manufactured according to Taguchi L_{27} orthogonal array by varying the levels of selected control parameters;
- d. Three-point bending test of specimens as per ASTM standard D 790;
- e. Flexural strength and flexure strain are measured and defined as quality characteristics of composite laminates;
- f. Statistical analysis is performed with the help of Signal to Noise (S/N) ratio to determine the significant effect of each variable on flexure properties;
- g. Optimized level of each parameter is determined;
- h. Validation of results is accomplished through predictive analysis.

2.2. The proposed framework

Product quality of composite products is defined in terms of mechanical, chemical, and physical properties such as ultimate strength, flexure strength, tensile strength, compressive strength, conformance to dimensions, voids, delamination, etc. [9]. The types of manufacturing equipment, specialized tooling, and inspection techniques have distinct effect on the design of composites. As the material is prepared during the part fabrication, concurrent engineering design approach, meticulous material, and production processes must be selected to get the required properties. Key design parameters are to be defined at the concept definition phase of the design cycle including calculation of maximum allowable loads, weight estimation, thickness, stress analysis, damage tolerance, etc. [10-12]. There are numerous process control variables involved in the manufacturing process that can be classified into three subgroups including material, in-process control parameters, and inspection techniques [1-6,9]. Quality Control (QC) and Quality Assurance (QA) parameters for in-process control variables are dependent on the manufacturing method used in developing a product. Each production method has specific tooling, laying procedure, and unique machines. Accordingly, the skill of labour, environmental conditions, storage, and handling procedures is varied. The manufactured composite parts must be checked for any damage/defects with the help of destructive and non-destructive tests. QC system ensures materials quality, control of process parameters, and procedure for testing to compare the end product properties with the desired design requirements [1,3,9]. QA of composites is ensured through conforming testing to guarantee the sustained reliability of a composite material, control parameters

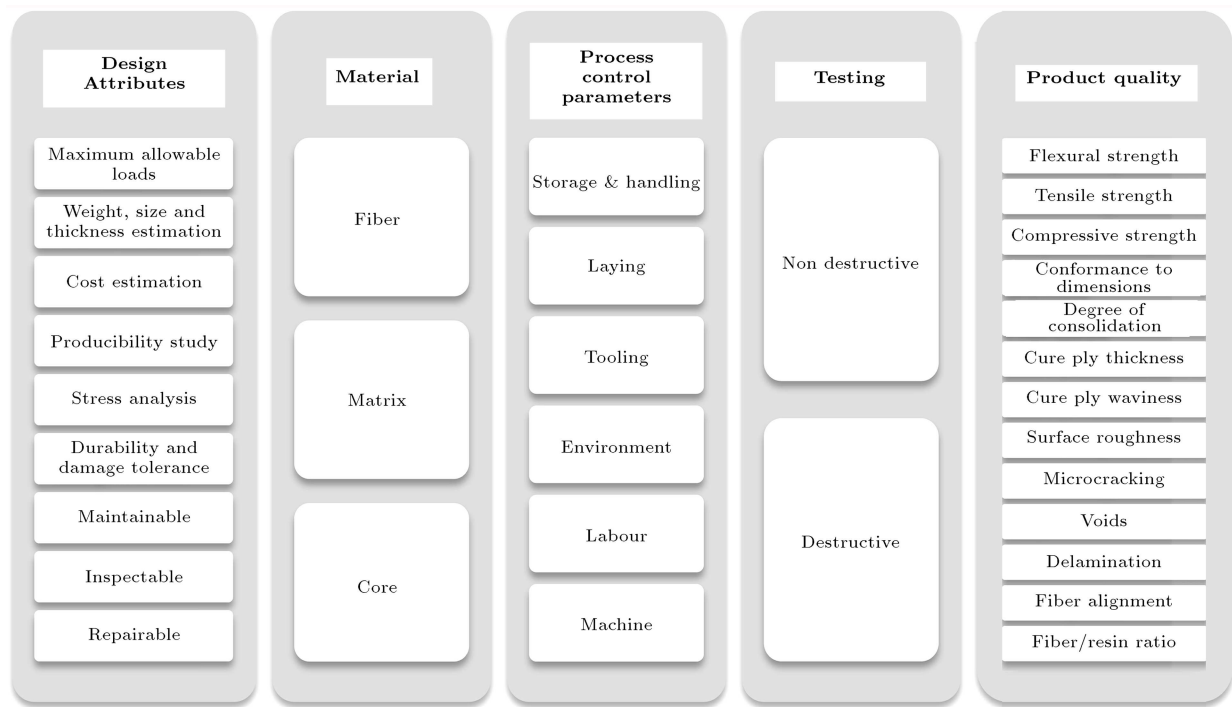


Figure 1. The proposed quality framework.

of process, and quality of finished parts [9,10]. Based on the literature, all key design parameters, manufacturing key variables, and product quality attributes are gathered and integrated into one framework as shown in Figure 1.

2.3. Selection of key variables

Desired product quality is required to be embedded right from the design stage. As an initial step, product and process specifications are defined and design attributes are estimated. Selection of appropriate materials, such as fiber type, matrix, and core, are finalized based on required technical characteristics. Subsequently, peculiar settings of process control parameters are ensured, and the product is produced as per laid down criteria. The product quality is then measured through a series of non-destructive and destructive testing procedures to validate the desired quality characteristics. For the purpose of this study, thirteen key variables from various stages of manufacturing, including design, material, and process control parameters, were selected to test the proposed framework. Weight and thickness were selected from design stage. Fiber type, matrix, and core type were chosen from the material. Resin hardening mixing time, viscosity, layup pattern, tooling, cure type, temperature, labour type and process technique were selected from the process control parameters. Accordingly, polymer composite sandwich laminates were produced by varying the values of these variables. Samples were tested through destructive testing technique (three-point bending),

and then flexural strength was calculated to measure the product quality.

3. Methodology

Taguchi method was applied to test the proposed framework. The approach follows a set pattern involving multi-stage sequential process to obtain the best results. Taguchi process is made up of four phases including the planning phase, experimental phase, data analysis phase, and validation phase. The planning phase is the most critical phase because the problem/objective, identification of control factors, and appropriate orthogonal array are selected and defined. In subsequent phases, data are collected from all the experiments and the effects of various process parameters on quality characteristics followed by optimum level determination and validation are analyzed [13-15]. Step-wise application of Taguchi method is shown in Figure 2.

3.1. Application of Taguchi method

Taguchi method is applied in the following steps:

- **Step 1: Problem Definition.** The first step in the Taguchi method is to determine the quality characteristic which is to be optimized. The quality characteristic is a parameter whose variation has a critical effect on product quality. It is an output or response variable to be observed. The objective of the proposed quality framework is to maximize the product quality of polymer composite products.

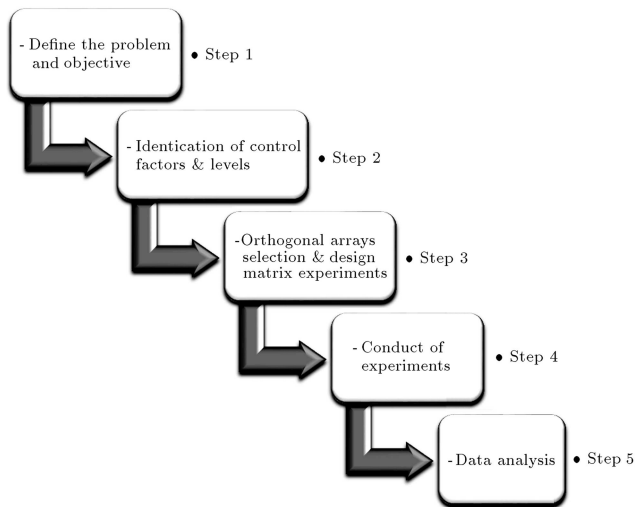


Figure 2. Flowchart representing step-wise Taguchi method.

The proposed quality framework highlights thirteen attributes of product quality (Figure 1). In the present study, flexure strength is selected to determine the product quality of polymer composites, and accordingly, the effects of process variables on flexure strength are studied. Therefore, flexure stress and flexure strain are defined as quality characteristics;

- **Step 2: Selection of control factors and corresponding levels.** The next stage is to categorize the control factors that influence the system performance and quality. Thirteen key parameters were selected including weight (A), thickness (B), fiber type (C), matrix (D), core type (E), resin hardening mixing time (F), viscosity (G), layup pattern (H), tooling (J), cure (K), temperature (L),

labour (M), and process technique (N). The values of each control parameter were varied at three levels. Control parameters along with each of three values are presented in Table 1.

- **Step 3: Selection of orthogonal array and experimental matrix.** Taguchi standardized orthogonal arrays were developed for various variables with corresponding levels [16]. L_{27} orthogonal array was selected from various sets of orthogonal arrays due to involvement of 13 parameters at each of 3 levels. The same is also verified through degrees of freedom approach with the help of Eq. (1) [17]. L_{27} array consists of 27 rows (experimental runs) and 13 columns (controlling parameters). Data of each parameter with corresponding levels are shown in Table 2.

$$N_{\text{Taguchi}} = \sum_{i=1}^{NV} (Li - 1), \quad (1)$$

where:

- N Number of experiments;
- NV Number of independent variables;
- L Number of levels of each variable.

- **Step 4: Conduct of experiments.** 27 composite sandwich laminates, each measuring 220×200 mm, were manufactured by varying levels of control parameters, as mentioned in Table 2. Sample photographs of laminates are shown in Figure 3. Three test specimens were derived from each laminate ($27 \times 3 = 81$) with the help of 4-axis universal milling machine model XQ6232WA according to dimensions, defined by ASTM standard D 790 [18].

Table 1. Experimental parameters and input levels.

Symbol	Description	Level 1	Level 2	Level 3
A	Weight	50 g	85 g	80 g
B	Thickness	5 mm	11 mm	10 mm
C	Fiber type	Unidirectional (UD)	Woven 3K filament (W3K)	Woven 1K Filament (W1K)
D	Matrix	Epoxy (EP)	Poly Epoxy (PE)	Polyester (PY)
E	Core type	Foam (FM)	Honey Comb 4 mm (HC 4)	Honey Comb 8 mm (HC 8)
F	Resin harden mixing time	0 minutes	6 minutes	12 minutes
G	Viscosity	900 mPa.s	1150 mPa.s	1650 mPa.s
H	Layup pattern	0° , 90°	0° , 45° , 90°	30° , 60° , 90°
J	Tooling	Carbon (CR)	Aluminum (AL)	Fiber Glass (FG)
K	Cure	Without Post Cure (WPC)	Post cure at 50°C (PC 50)	Post cure at 70°C (PC 70)
L	Temperature	15°C	22°C	30°C
M	Labour	X	Y	Z
N	Process technique	Wet Lay up (WL)	Vacuum Bagging (VB)	Vacuum Infusion (VI)

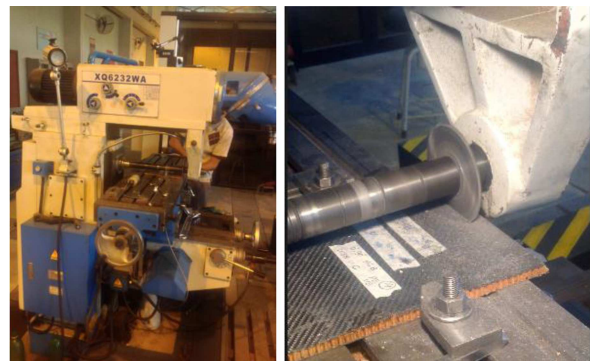
Table 2. L_{27} Orthogonal array with the corresponding values of each parameter.

Run	A	B	C	D	E	F	G	H	J	K	L	M	N
1	50	5	UD	EP	HC 4	0	900	0, 90	CR	WPC	15	X	WL
2	50	5	UD	EP	FM	6	1150	0, 45, 90	AL	PC 50	22	Y	VB
3	50	5	UD	EP	HC 8	12	1650	30, 60, 90	FG	PC 70	30	Z	VI
4	50	11	W3K	PE	HC 4	0	900	0, 45, 90	AL	PC 50	22	Y	VI
5	50	11	W3K	PE	FM	6	1150	30, 60, 90	FG	PC 70	30	Z	WL
6	50	11	W3K	PE	HC 8	12	1650	0, 90	CR	WPC	15	X	VB
7	50	10	W1K	PY	HC 4	0	900	30, 60, 90	FG	PC 70	30	Z	VB
8	50	10	W1K	PY	FM	6	1150	0, 90	CR	WPC	15	X	VI
9	50	10	W1K	PY	HC 8	12	1650	0, 45, 90	AL	PC 50	22	Y	WL
10	85	5	W3K	PY	HC 4	6	1150	30, 60, 90	CR	PC 70	22	Z	WL
11	85	5	W3K	PY	FM	12	1650	0, 90	AL	WPC	30	X	VB
12	85	5	W3K	PY	HC 8	0	900	0, 45, 90	FG	PC 50	15	Y	VI
13	85	11	W1K	EP	HC 4	6	1150	30, 60, 90	AL	WPC	30	X	VI
14	85	11	W1K	EP	FM	12	1650	0, 90	FG	PC 50	15	Y	WL
15	85	11	W1K	EP	HC 8	0	900	0, 45, 90	CR	PC 70	22	Z	VB
16	85	10	UD	PE	HC 4	6	1150	30, 60, 90	FG	PC 50	22	X	VB
17	85	10	UD	PE	FM	12	1650	0, 90	CR	PC 70	22	Z	VI
18	85	10	UD	PE	HC 8	0	900	0, 45, 90	AL	WPC	30	X	WL
19	80	5	W1K	PE	HC 4	12	1650	0, 45, 90	CR	PC 50	30	Y	WL
20	80	5	W1K	PE	FM	0	900	30, 60, 90	AL	PC 70	15	Z	VB
21	80	5	W1K	PE	HC 8	6	1150	0, 90	FG	WPC	22	X	VI
22	80	11	UD	PY	HC 4	12	1650	0, 45, 90	AL	PC 70	15	Z	VI
23	80	11	UD	PY	FM	0	900	30, 60, 90	FG	WPC	22	X	WL
24	80	11	UD	PY	HC 8	6	1150	0, 90	CR	PC 50	30	Y	VB
25	80	10	W3K	EP	HC 4	12	1650	0, 45, 90	FG	WPC	22	X	VB
26	80	10	W3K	EP	FM	0	900	30, 60, 90	CR	PC 50	30	Y	VI
27	80	10	W3K	EP	HC 8	6	1150	0, 90	AL	PC 70	15	Z	WL

**Figure 3.** Sample of composite sandwich laminates.

The pictures of milling machine/cutting operation and test specimens are shown in Figures 4 and 5, respectively. Each test specimen was subjected to three-point bend loading through ShimadzuTM UTM (20 kN) autograph AG-X plus, as shown in Figure 6.

Load was applied to each specimen at specified crosshead rate; accordingly, load deflection data, including maximum flexure stress, corresponding strain, and load deflection curve, were recorded simultaneously with the help of integrated Trapezi-

**Figure 4.** Universal milling machine and cutting operation.

umx software connected with universal testing machine. Failure pattern of different specimens is shown in Figure 7.

- **Step 5: Data analysis.** Values of maximum flexural stress and corresponding strain for all 81

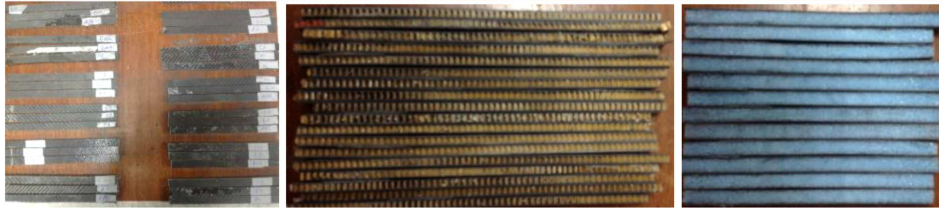


Figure 5. Test specimens.

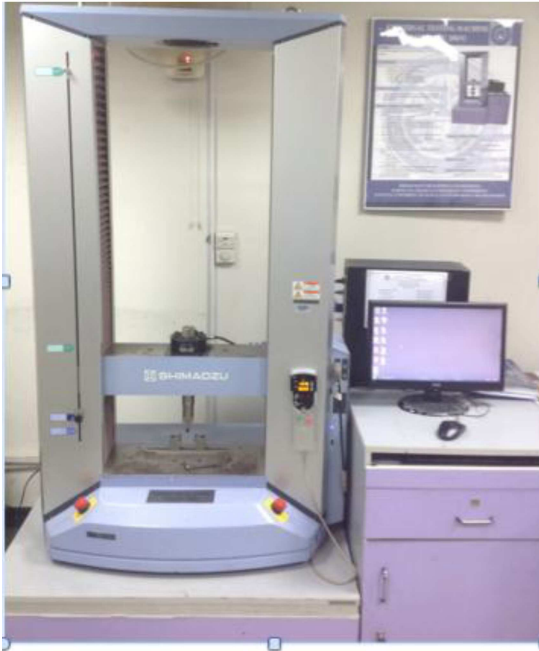


Figure 6. Universal testing machine with three-point bend set up.

samples were calculated as per Eqs. (2) and (3), respectively [18]. Minitab software version 18 was used for statistical analysis:

$$\sigma_f = 3PL/2bd^2, \quad (2)$$

$$\varepsilon_f = 6Dd/L^2, \quad (3)$$

where:

σ_f Flexure stress in the outer fibers at midpoint, N/mm^2

P Load at a given point on the load-deflection curve, N

L Support span, mm

b Width of beam tested, mm

d Depth of beam tested, mm

ε_f Flexure strain in the outer surface, mm/mm

D Maximum deflection of the center of the beam, mm

The results are analysed through Signal-to-Noise (S/N) ratio extracted from electrical control theory. The S/N ratio is measured by calculating mean and variation; therefore, it is the ratio of signal (mean) to the noise (standard deviation) [19]. Three S/N ratios are commonly used in Taguchi method including situations in which the required characteristics are either bigger the best (strength), smaller the best (vibrations), or nominal the best (dimensions). In this study, bigger the best was selected for measuring flexure stress S/N_σ ratio (Eq. (4)), whereas smaller the best was selected for measuring flexure strain S/N_ε ratio (Eq. (5)) [19]. Data of flexure stress and corresponding strain against each experiment



Figure 7. Failure patterns of different specimens and load deflection curve.

Table 3. Values of flexure stress, flexure strain, and S/N ratio.

Laminate	Flexure stress (N/mm ²)					Flexure strain %				
	Sample	Sample	Sample	Mean	S/N_σ	Sample	Sample	Sample	Mean	S/N_ϵ
	1	2	3			1	2	3		
1	50.719	55.042	55.572	53.771176666	34.589	3.366	2.262	3.585	3.071	5.407
2	38.138	35.226	40.126	37.83	31.519	1.604	1.343	1.563	1.503333333	9.212
3	6.177	8.14	5.075	6.464	15.733	5.04	5.14	4.965	5.048333333	2.274
4	16.662	15.979	25.225	19.28866667	25.185	1.382	2.137	1.986	1.835	2.800
5	1.457	1.689	2.357	1.834333333	4.764	4.959	0.471	0.457	1.962333333	1.701
6	15.387	15.388	19.605	16.79333333	24.338	1.335	1.335	1.225	1.298333333	1.682
7	29.482	34.602	40.596	34.89333333	30.634	0.732	0.68	0.759	0.723666667	1.0382
8	44.241	34.697	54.241	44.393	32.514	0.792	0.7	0.954	0.815333333	9.526
9	58.044	60.265	50.983	56.43066667	34.962	1.164	1.343	1.123	1.21	1.309
10	14.728	16.634	10.689	14.017	22.472	1.222	0.802	0.475	0.833	2.049
11	6.029	6.03	1.457	4.505333333	7.560	1.023	1.125	4.959	2.369	1.139
12	8.5786	1.587	7.401	5.855533333	8.447	1.587	0.351	1.189	1.042333333	0.222
13	23.797	25.747	39.335	29.62633333	28.837	0.637	0.691	0.994	0.774	2.938
14	41.581	38.905	43.657	41.381	32.306	0.972	0.836	0.815	0.874333333	10.991
15	49.099	43.922	55.205	49.40866667	33.763	0.865	0.883	1.15	0.966	7.940
16	82.347	94.134	102.832	93.10433333	39.270	1.324	1.41	1.47	1.401333333	2.233
17	39.742	56.485	20.243	38.82333333	29.473	5.00	3.467	0.8191	3.095366667	5.920
18	32.605	23.255	23.255	26.37166667	28.107	1.784	2.783	2.783	2.45	4.748
19	36.211	52.807	41.531	43.51633333	32.464	1.316	1.205	1.354	1.291666667	4.602
20	16.655	7.742	5.886	10.09433333	17.855	1.098	2.137	2.44	1.891666667	0.848
21	60.186	54.838	68.055	61.02633333	35.609	1.5	2.278	1.23	1.669333333	2.737
22	11.402	10.537	10.537	10.82533333	20.671	1.186	1.904	1.904	1.664666667	4.436
23	40.876	52.233	39.528	44.21233333	32.716	0.831	0.997	1.401	1.076333333	9.356
24	68.263	75.123	68.866	70.75066667	36.970	0.844	0.743	0.577	0.721333333	0.850
25	7.985	7.468	18.723	11.392	19.152	0.987	0.897	2.56	1.481333333	5.407
26	17.584	18.608	25.345	20.51233333	25.918	2.684	2.941	3.165	2.93	9.212
27	8.078	3.851	3.85	5.259	13.003	0.805	1.225	1.225	1.085	2.274

are presented in Table 3.

$$S/N_\sigma = -10 * \log\{\Sigma(1/Y^2)/n\}, \quad (4)$$

$$S/N_\epsilon = -10 * \log\{\Sigma(Y^2)/n\}, \quad (5)$$

where:

S	Signal
N	Noise
Y	Mean of sum of square
n	Number of samples

After determination of S/N ratio for each experiment, the S/N ratio of each control parameter was calculated. S/N_σ ratio of flexure stress computed for each control parameter is tabulated in Table 4,

whereas S/N_ϵ ratio of flexure strain computed for each control parameter is shown in Table 5. Ranking of S/N ratios was done according to the amount of variation produced by each control parameter in response variables (flexure stress and strain). Maximum variation of S/N ratio at three levels in the given parameter means significant impact on response variable, and vice versa. Corresponding graphs highlighting variation of each control parameter are shown in Figures 8 (flexure stress) and 9 (flexure strain).

4. Results and discussion

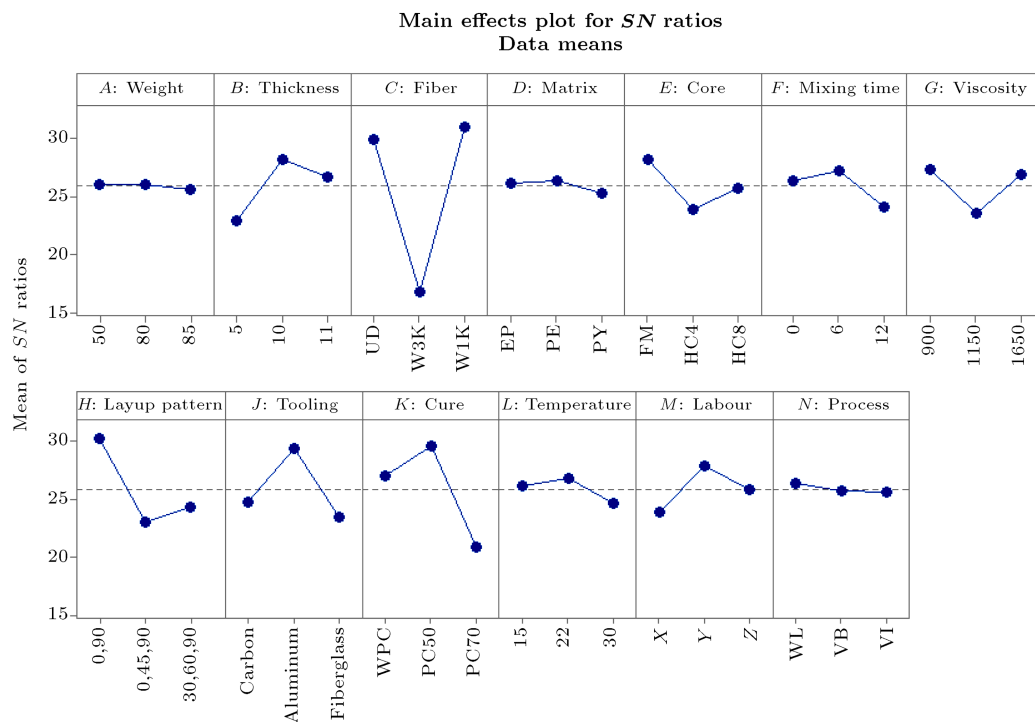
It is inferred from Table 4 and Figure 8 that fiber pattern, cure, type of tooling, and layup pattern are

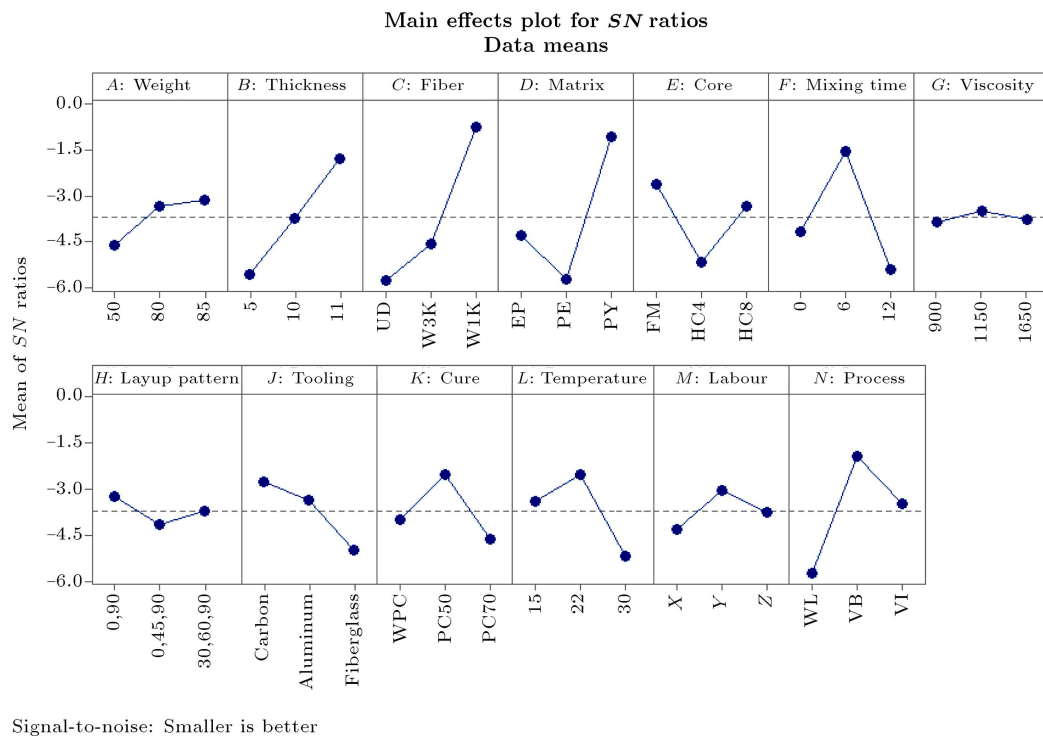
Table 4. Response table for S/N_σ ratio of flexure stress.

Levels	Weight	Thickness	Fiber pattern	Matrix	Core	Mixing time	Viscosity	Layup pattern	Tooling	Cure	Temperature	Labour	Process
1	25.6	25.6	30.2	26.2	27.5	28.0	28.7	30.3	27.0	27.7	26.6	25.5	26.8
2	26.9	28.8	18.9	27.0	25.4	27.4	24.5	25.3	29.6	30.3	27.9	28.0	27.1
3	27.9	26.1	31.3	27.2	27.5	25.0	27.2	24.8	23.8	22.3	25.8	26.9	26.4
Delta	2.37	3.21	12.4	0.99	2.07	3.01	4.15	5.44	5.75	8.01	2.08	2.49	0.68
Rank	9	6	1	12	11	7	5	4	3	2	10	8	13

Table 5. Response table for S/N_ε ratio of flexure strain.

Levels	Weight	Thickness	Fiber pattern	Matrix	Core	Mixing time	Viscosity	Layup pattern	Tooling	Cure	Temperature	Labour	Process
1	4.62	5.58	5.79	4.30	2.62	4.18	3.86	3.22	2.77	3.99	3.38	4.29	5.74
2	3.36	3.74	4.59	5.74	5.17	1.53	3.48	4.16	3.38	2.51	2.54	3.05	1.91
3	3.13	1.79	0.74	1.07	3.32	5.40	3.77	3.73	4.97	4.62	5.19	3.77	3.46
Delta	1.48	3.78	5.04	4.66	2.55	3.87	0.37	0.93	2.19	2.10	2.64	1.23	3.83
Rank	10	5	1	2	7	3	13	12	8	9	6	11	4

**Figure 8.** S/N_σ ratio graph for flexure stress.

**Figure 9.** S/N_e ratio graph for flexure strain.

the most significant variables affecting flexure stress, while weight of laminate, type of process technique used, type of matrix, and temperature variation are relatively insignificant. Optimal control parameters for flexure stress were achieved at level 2 of weight (80 g), level 2 of thickness (10 mm), level 3 of fiber pattern (W1K), level 2 of matrix (PE), level 1 of core (foam), level 2 of resin hardening mixing time (6 min), level 1 of viscosity (V1), level 2 of layup pattern (0° , 90°), level 2 of tooling (aluminium), level 2 of cure (PC 50), level 2 of temperature (22°C), level 2 of labour (Y), and level 1 of process (wet layup). Therefore, optimum level combination of control parameters determined for flexures stress is A2B2C3D2E1F2G1H1J2K2L2M2N1.

It is inferred from Table 5 and Figure 9 that fiber pattern, matrix type, resin hardening mixing time, and process techniques have significant effect on flexure strain, while viscosity, layup pattern, labour, and laminate weight have relatively insignificant effect. Optimal control parameters for flexure strain were achieved at level 3 of weight (85 g), level 3 of thickness (11 mm), level 3 of fiber pattern (W1K), level 3 of matrix (PY), level 1 of core (FM), level 2 of resin hardening mixing time (6 min), level 2 of viscosity (1150 mPa.s), level 1 of layup pattern (0° , 90°), level 1 of tooling (carbon), level 2 of cure (PC 50), level 2 of temperature (22°C), level 2 of labour (Y) and level 2 of process (vacuum bagging). Therefore, optimum level combination of control parameters determined for flexures strain is A3B3C3D3E1F2G2H1J1K2L2M2N2.

Results of experiments showed that fiber pattern is the most significant parameter for both flexure stress and strain. Cure agent and layup pattern are significant for flexure stress, but relatively insignificant in the case of strain. Variation in viscosity is significant in flexure stress, but highly insignificant in strain. Variation in laminate thickness and labour type is significant and has almost the same effect on both stress and strain. Variation in resin hardening mixing time is more pronounced in strain. Change of weight has not contributed much in flexural properties, whereas variation in temperature, matrix, and core material has more influence on strain compared to stress. Process technique used was insignificant in stress, but highly significant in the case of strain. It is an important finding that the optimal levels of 7 variables, including fiber pattern, core type, mixing time, layup pattern, cure, temperature, and labour, are the same for both flexure stress and strain.

4.1. Validation of results

Results obtained are confirmed through validation experiment. The optimal levels of each parameter obtained through experiments were selected, and confirmatory run was performed. The results of validation experiment confirmed the authenticity of optimal parameters, as shown in Table 6. Maximum value of flexure stress (97.134 N/mm) and minimum value of flexure strain (0.435%) were achieved, implying that the selected control parameters are the best to produce

Table 6. Results of validation experiment.

Response variable	Optimal parameter levels	S/N	Mean	SD
Flexure Stress	A2B2C3D2E1F2G1H1J2K2L2M2N1	49.674	97.134 (N/mm ²)	9.132
Flexure Strain	A3B3C3D3E1F2G2H1J1K2L2M2N2	4.585	0.435%	0.213

polymer composite sandwich laminate structures with high stress and low strain values. The optimized levels of various parameters are useful for application in aviation, mechanical, sand civil industries where flexure properties are frequently encountered during operations.

5. Conclusion

This paper presents a novel quality framework for polymer composite manufacturing industries. It is concluded from the results that fiber pattern, post cure, tooling type, and layup pattern are the most significant parameters affecting flexure stress, whereas fiber pattern, matrix type, resin and hardener mixing time, and process techniques are the most significant parameters affecting flexure strain. Optimized values of flexure stress and flexure strain are obtained. Findings of this study are useful for polymer composite application in aviation, mechanical, sports, and civil industries. The optimized levels could be used in each industry depending upon the flexural requirements or life cycle use of products. Finally, the following areas of future research are proposed;

- To test and evaluate the proposed framework by selecting various combinations of control factors with more numbers of level;
- To test other quality characteristics of polymer composite, such as compressive strength, tensile strength, void, etc., and study the significance of control parameters on these attributes;
- To analyse interaction effect of significant control parameters on response variables through ANOVA study, and accordingly, mathematical models could be developed;
- Other process variables, design attributes, and material parameters may be added to the framework, and their significance of quality attributes arises to be evaluated.

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