Optimizing the material composition for a wind turbine blade using grey based Taguchi technique

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Abstract: The aim of this proposal is to fabricate a best polymer composite material for a wind turbine blade. In order to obtain a feasible composite, the material compositions were optimized using grey based Taguchi technique. For the investigation, experiments were conducted by using Taguchi (L18) orthogonal array. Analysis of variance was used to find the significant parameter which determines the mechanical properties. The result reveals that 5 wt% of SiC improves the mechanical properties of the composite.
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1. Introduction

Fibre reinforced polymers are mostly organized in the form of laminates structure. Each layer is composed of unidirectional or woven fabric embedded within a thin film of polymer matrix. The use of composite laminates like carbon fibre reinforced polymers, in complex structures has increased significantly from the last decades. Reasons for this could be some unique properties like low weight, high strength and stiffness (Kishore et al., 2009). As wind turbine manufacturers Vestas and Gamesa are using carbon fibre in their blades, the whole wind turbine system cost is less than an equivalent system made up of only glass fibres. Fatigue stresses will also be created on wind turbine components due to rotation. (Thresher, Laxson A,2006) reported that blade mass can also be reduced by using more carbon fibres.(Juliane Mentz et al.,2006) evaluated the mechanical properties of carbon fibre reinforced silicon carbide composites prepared by a novel processing method. They observed a fibre dominated behavior due to high strength of carbon fibres and matrix porosity. (Rashedi et al., 2012) explored material selection strategies for a wind turbine blade and its tower based on multiple constraints and conflicting objectives. (Cheng-Huat Ong, Stephen W.Tsai, 2000) evaluated the benefit of using carbon fibres in a wind turbine blade. Their study indicates that, if large amount of carbon fibre composites were used in blades, then the performance of blades will also increase due to less weight of carbon fibres and low skin thickness of blade. (Christoph W. Kensche,2006) suggests that carbon fibre reinforced composites could be an alternative to glass fibre reinforced composites for large commercial wind turbine blades; as carbon fibres are much stiffer, lighter and have good fatigue properties. Isoresins exhibit higher thermal and dimensional stability with better creep resistance. Also, they are cheaper than epoxy resins. Silicon carbide has high strength and modulus; particulates of silicon carbide are used as fillers to improve the isotropic properties of the composite. The capital investment for manufacturing a polymer composite is less in hand lay-up method (Antonio FA, David TS. Morais, 2005).

Unfilled thermoset polymers tend to become hard and brittle. So, multiple phases such as fillers, modifiers, are added with thermosetting polymers to improve their physical properties. Inorganic ceramic fillers can improve tensile strength, stiffness, abrasion resistance and dimensional stability. Researchers have also observed that these inorganic ceramic fillers can affect cure exotherms, shrinkage, thermal and electrical conductivity, machinability, hardness, compressive, flexural and impact strength. Better properties will be obtained for a composite, if there is uniform dispersion of filler; as well as good degree of interaction between filler and the matrix. An ideal performance is achieved with inorganic fillers consisting of small particles that are uniformly dispersed throughout the matrix. These fillers will also interact strongly with the organic matrix (Kumaresan et al., 2011, Jansen et al.,1999, Harani et al., 1999).(Subbaya et al., 2012) developed carbon fabric reinforced epoxy composites by varying the weight fraction of silicon carbide filler. Grey-based Taguchi approach has been adopted to optimize the tribological properties. Taguchi method combined with the grey relational analysis is used to improve the yield of chrome thin-film sputtering process of the black matrix in color filter manufacturing. The confirmation experiment verifies that, the proposed grey-based Taguchi method has the ability to find the optimal process parameters with multiple quality characteristics (Yu-Min Chiang, 2009).

The present investigation is to develop best carbon fibre reinforced polymer composite suitable for wind turbine application. The material composition is optimized by using grey relation based Taguchi method.

2. Optimization using Taguchi based grey relation method

Taguchi method is a powerful tool for the design of a high-quality system. This method provides a systematic approach to minimize the number of experiments and to optimize the process parameter for better performance and quality (Lung Kwang Pan et al., 2007) The S/N ratio is used to find the better performance of the process parameter, which attributes quality characteristics. The S/N ratio performance characteristics are divided into smaller the better, nominal the best and larger the better categories. In order to optimize the process parameters, larger the better quality characteristic is selected to maximize the tensile strength, flexural strength and impact strength. The loss function for the higher-the-better performance characteristic can be expressed in equation (1) as:

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ij}^{2}} \qquad (1)$$

where, L_{ij} is the loss function of the i^{th} performance characteristic in the j^{th} experiment, y_{ijk} the experimental value of the i^{th} performance characteristic in the j^{th} experiment at the k^{th} trial, and n the number of trials.

The loss function is further transformed into a S/N ratio. (Tosun N et al., 2004) reported that in Taguchi method the deviation of the performance characteristic from the desired value is determined by the S/N ratio. The S/N ratio η_{ij} for the ith performance characteristic in the jth experiment can be expressed in equation (2) as:

$$\eta_{ij} = -10 \log (L_{ij}) \qquad (2)$$

This method is applicable to optimize single response characteristic problem. Grey relational analysis is used to solve multi-attribute decision making problems. This method combines the entire range of performance attribute values being considered for every alternative, into one single value (Suman Kalyan Das et al., 2011). In this, the S/N ratio is first normalized into a range between zero and unity (Tarng YS et al., 2002). The normalized S/N ratio χ_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be expressed in equation (3) as:

$$\chi_{ij} = \frac{\eta_{ij} - \min \eta_{ij}}{\max \eta_{ij} - \min \eta_{ij}} \qquad (3)$$

Where χ_{ij} is the value after the grey relational generation, min η_{ij} is the smallest value η_{ji} of the j^{th} response, and max η_{ij} is the largest value of η_{ij} for the j^{th} response. Then using the normalized value the grey relation coefficient is determined. The grey relational coefficient ζ_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be expressed in equation (4) as:

$$\zeta_{ij} = \frac{\min_i \min_j \left|\chi_i^0 - \chi_{ij}\right| + \zeta \max_i \max_j \left|\chi_i^0 - \chi_{ij}\right|}{\left|\chi_i^0 - \chi_{ij}\right| + \zeta \max_i \max_j \left|\chi_i^0 - \chi_{ij}\right|} \qquad (4)$$

where χ^0_i is the ideal normalized S/N ratio for the i^{th} performance characteristic and ζ the distinguishing coefficient which is defined in the range $0 \le \zeta \le 1$.The grey relation grade is obtained by averaging the grey relation coefficient.The grey relational grade γ_j can be obtained from equation (5):

$$\gamma_j = \frac{1}{m}\sum_{k=1}^{n} w_i \zeta_{ij} \qquad (5)$$

where γ_j is the grey relational grade for the j^{th} experiment, w_i the weighting factor for the i^{th} performance characteristic, and m the number of performance characteristics. These results reveal that the complex multiple performance characteristics can be converted into a single response grey relation grade.

The main purpose of using analysis of variance (ANOVA) in this study is to identify the effect of individual factors. ANOVA results evidently provide the influence of each factor on the process performance.

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3. Experimental Setup

3.1 Material

Unidirectional carbon fibre mat used in this study was obtained from Kemrock Industries and exports ltd. Vadodara.India. Epoxy resin, isoresin and Silicon carbide were obtained from Sakthi fibers. The properties of the fiber are given in Table.1.

Table 1. Properties of carbon fibre

Properties	Ranges
Tensile Strength(GPa)	2.0 - 3.0
Tensile Modulus(GPa)	180 - 250
Elongation(%)	1.0 - 1.5
Density(gm/cm^3)	1.73 - 1.78
Filament Diameter(Micron)	7 - 8
Sizing Content(%)	<1.5
Carbon Content (%)	>93
Mass per unit Length(g/m)	0.8-0.85

Table 2. Properties of Silicon carbide

Properties	Ranges
Density	3210 kg/m^3.
Filling mass	1251–1410 kg/m^3.
Particle size	6–10 µm.

3.2 Composite Fabrication

The material composition and their levels are given in Table 3. The L18 orthogonal array is selected as per standards suggested by Taguchi approach (Lakshminarayanan AK. and Balasubramanian V, 2008).It is shown in Table 4.

Table 3. Parameters and their Levels

Process Parameter/Level	Low (1)	Medium (2)	High (3)
Resin	IR	-	ER
Filler Material (wt %)	0	5	10
Fiber Material (wt %)	50	52.5	54.5

Table 4. L18 Orthogonal array

Ex. No	Resin	Filler Material	Fiber Material
1	IR	1	1
2	IR	1	2
3	IR	1	3
4	IR	2	1
5	IR	2	2
6	IR	2	3
7	IR	3	1
8	IR	3	2
9	IR	3	3
10	ER	1	1
11	ER	1	2
12	ER	1	3
13	ER	2	1
14	ER	2	2
15	ER	2	3
16	ER	3	1
17	ER	3	2
18	ER	3	3

To remove the absorbed moisture and prevent void formation, carbon fibre mat was dried at 110℃ for five hours. Six layers of untreated carbon fibre square mat were used. The hand lay-up technique was used for the preparation of the five types of composites. The silicon carbide filler was treated with 2% organo-reactive silane coupling agent. The epoxy matrix was prepared in three different compositions by varying the weight fraction of silicon carbide such as 0%, 5% and 10% with the aliphatic amine hardner. This modified epoxy resin is applied on a 4mm deep mould. One layer of carbon fibre mat was placed over the epoxy resin; then, a hand roller is rolled over the mat rigorously to enhance mutual adherence between resin and the mat. This will also remove the air bubbles; if present, in the resin. The laminar composite was thus prepared with all the six layers having 0°ply angle. It was kept under pressure in compression moulding machine for twenty four hours, to obtain partial curing of the resin. It was then cured at 80℃ for four hours. Similarly, another two laminar composites each having six layers and 0°ply angle was also prepared in isoresin matrix by varying the weight fraction of silicon carbide (0% and 5%) using the catalyst methyl ethyl ketone peroxide and the accelerator cobalt napthanate. The tensile, flexural and impact test specimens were prepared as per ASTM D638, ASTM D790, ASTM D7136 standards respectively. The results of the test support to optimize the material composition.

4. Result & Discussions

4.1 S/N Ratio

The calculated S/N ratio for the experimental results are given in Table 5. It was observed that, the parameter level may be varied for different performance characterization. Hence, multi response characterization index is necessary for optimization. In this investigation, complex S/N values are used in grey relation analysis for optimizing the multi objective problem. Table 6. shows the normalized S/N ratio and grey relation coefficient for mechanical properties of the prepared composites. Generally, larger normalized value exhibits better performance and the best normalized value is equal to one (Deng JL,1989). Grey relation coefficient shows the relationship between ideal and the measured value (Narender Singh P et al., 2004).The grey relation grade for each experiment was calculated and the results were given in Table 5. It was observed that experiment 6 shows the best multiple performance characteristics when compared with other 17 experiments. Table 7 shows the total mean grey relation grade and mean for each level of the process parameters. The optimal level of the three combinations is illustrated in the Figure 5.

Table 5. Experimental Result and S/N Ratio

Exp. No	Resin	Filler	Fiber	TS (Mpa)	FS (Mpa)	IS (J)	S/N of TS	S/N of FS	S/N of IS
1.	IR	0	50	456.8	218	12.7	53.195	46.769	22.076
2.	IR	0	52.5	553.76	207	16.2	54.866	46.319	24.190
3.	IR	0	54.5	692	196.4	20.6	56.802	45.863	26.277
4.	IR	5	50	682	231	25.4	56.676	47.272	28.097
5.	IR	5	52.5	745.5	225.9	24	57.449	47.078	27.604
6.	IR	5	54.5	863.6	211	22.8	58.726	46.486	27.159
7.	IR	10	50	643.72	229.6	21.1	56.174	47.219	26.486
8.	IR	10	52.5	711	221	24.6	57.037	46.888	27.819
9.	IR	10	54.5	791.7	216	21.4	57.971	46.689	26.608
10.	ER	0	50	578	233.7	6.6	55.239	47.373	16.391
11.	ER	0	52.5	664	227.2	7.4	56.443	47.128	17.385
12.	ER	0	54.5	744.5	220.3	9.49	57.437	46.860	19.545
13.	ER	5	50	773	189	6.8	57.764	45.529	16.650
14.	ER	5	52.5	873.73	181	10.22	58.828	45.154	20.189
15.	ER	5	54.5	994	175	13.6	59.948	44.861	22.671
16.	ER	10	50	778.6	192.4	10	57.826	45.684	20.000
17.	ER	10	52.5	840	184	11.5	58.486	45.296	21.214
18.	ER	10	54.5	931.4	178	12.3	59.383	45.008	21.798

4.2 Grey Relation Analysis

Table 6. Normalized, Coefficient and grade of TS, FS and IS

S/N of TS	Normalize	Coeffcient	S/N of IS	Normalize	Coeffcient	S/N of FS	Normalize	Coeffcient	Grade
53.195	0.000	0.500	22.076	0.486	0.660	46.769	0.760	0.806	0.656
54.866	0.247	0.571	24.190	0.666	0.750	46.319	0.580	0.704	0.675
56.802	0.534	0.682	26.277	0.845	0.865	45.863	0.399	0.625	0.724
56.676	0.515	0.674	28.097	1.000	1.000	47.272	0.960	0.961	0.878
57.449	0.630	0.730	27.604	0.958	0.960	47.078	0.883	0.895	0.861
58.726	0.819	0.847	27.159	0.920	0.926	46.486	0.647	0.739	0.837
56.174	0.441	0.641	26.486	0.862	0.879	47.219	0.939	0.942	0.821
57.037	0.569	0.699	27.819	0.976	0.977	46.888	0.807	0.838	0.838
57.971	0.707	0.774	26.608	0.873	0.887	46.689	0.728	0.786	0.816
55.239	0.303	0.589	16.391	0.000	0.500	47.373	1.000	1.000	0.696
56.443	0.481	0.658	17.385	0.085	0.522	47.128	0.902	0.911	0.697
57.437	0.628	0.729	19.545	0.269	0.578	46.860	0.796	0.830	0.712
57.764	0.677	0.756	16.650	0.022	0.506	45.529	0.266	0.577	0.613
58.828	0.834	0.858	20.189	0.324	0.597	45.154	0.117	0.531	0.662
59.948	1.000	1.000	22.671	0.536	0.683	44.861	0.000	0.500	0.728
57.826	0.686	0.761	20.000	0.308	0.591	45.684	0.328	0.598	0.650
58.486	0.784	0.822	21.214	0.412	0.630	45.296	0.173	0.547	0.666
59.383	0.916	0.923	21.798	0.462	0.650	45.008	0.059	0.515	0.696

Table 7. Response Table for Mean of grey grade

Parameter/ Level	1-Mean	2-Mean	3-Mean
Resin	0.7896	-	0.6800
Filler Material	0.6933	0.7632	0.7478
Fiber Material	0.7190	0.7332	0.7522
Total	2.2019	1.4963	2.1800
Mean Grey	0.7348		

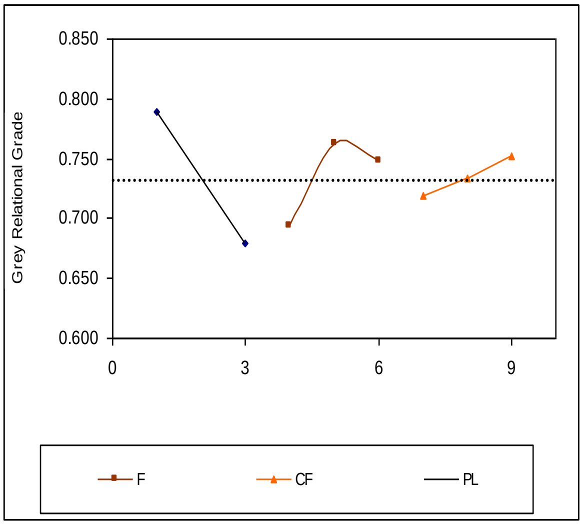

Figure 5. Grey Relation Grade

4.3 ANOVA

In this study, ANOVA was used to investigate the significance of process parameters on performance characteristics. Table 8. shows the results of ANOVA for grey relation grade values. In this context, the parameter resin plays a major role on the performance characteristics and predecessor by carbon fiber volume percentage. The analysis shows that the optimal process combination for fabricating a best polymer composite is isoresin with filler material of 5 wt% (level 2) and carbon fiber of 54.5 wt% (level 3).

Table 8. ANOVA for Grey Grade

Parameter/ Level	DOF	SSQ	MEANS Q	F	P	%
Resin	6	0.0540	0.0090	0.1999	0.4557	45.5715
Filler Material	6	0.0162	0.0027	0.0598	0.1364	13.6384
Fiber Material	5	0.0433	0.0077	0.1148	0.3280	2.8041
Error		0.0450				7.9860
	17					100.0000

5. Conclusion

If the cost of carbon fibres could be reduced by using a cheaper precursor and an efficient manufacturing process then carbon fibre composites would be the optimal material for many applications. The grey based Taguchi method was used in this investigation to optimize the process combination for fabricating best polymer composites. The results are summarized as follows:

- It was observed that, the optimized combination for fabricating a best polymer composite is isoresin with filler material of 5 wt% and carbon fibre of 54.5 wt%.
- The ANOVA results emphasis that, the parameter resin contribution was 45.57 % and it has more influence on the properties of the best polymer composite.

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