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FACTORIAL DESIGN OF EXPERIMENT VS. TAGUCHI APPROACH IN FILAMENT WOUND COMPOSITES

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Abstract *Main purpose of this paper is to present a valid comparison between full factorial design of experiment (2^2) and Taguchi approach (L_4) in determination of the influence of manufacturing parameters on hoop tensile strength and hoop tensile modulus of carbon fiber/epoxy resin NOL ring samples. Samples were manufactured with filament winding technology with winding speed and winding tension as control parameters and tested on universal testing machine. Results received from mechanical tests represented with factorial design of experiment were in good correlation with results received from Taguchi method.*
Key words: *filament winding, hoop tensile strength, hoop tensile modulus, NOL ring samples.*

1 INTRODUCTION

Composite materials are finding various applications in different industries due to their advantages which include lighter weight, improved fatigue life, the ability to design the final product for optimum strength and stiffness, corrosion resistance and reduced assembly costs due to fewer detail parts and fasteners [1, 2].

In composite parts produced with filament winding technology many factors can influence on mechanical properties of final part. In order quantitatively to determine how many factors and their interaction impact on the end product, design of experiment (DOE) can be used [3, 4]. Another method to investigate how different parameters affect the mean and variance of a process performance is Taguchi method, where instead of having to test all possible combinations like factorial design of experiment, pairs of combinations are tested [5, 6].

In this paper has been given a comparison between factorial DOE and Taguchi method in determination of parameter influence on hoop tensile strength and hoop tensile modulus of carbon fiber/epoxy resin NOL ring samples.

2 MATERIALS AND METHODS

For the manufacture of NOL ring samples were used carbon fiber T700S 24K from Toray and three component epoxy resin system Araldite® LY1135-1/ Aradur® 917/ Accelerator 960 from Huntsman. Wet filament winding process was conducted on laboratory filament winding machine MAW FB 6/1 manufactured by Mikrosam AD. For more precise control on fiber tension, electrical creel was used. From the creel carbon fiber was transported to roller impregnation bath with resin temperature of 37°C and finally it was wound on rotational mandrel specially designed for manufacture of NOL ring samples according to ASTM D2290 standard [7]. All samples were manufactured with 146 mm inside diameter, 22.86 mm width and 3 mm thickness with parameters given in Table 1 and constant resin mass fraction of 25 w% during winding.

Table 1: Level of control parameters

Symbol	Winding parameter	Parameter level	
		1	2
V (x_1)	Winding speed (m/min)	3.5	10
F (x_2)	Fiber tension (N)	20	85

Mechanical tests were performed on universal testing machine AG-Xplus Series from Shimadzu with maximal load of 250 kN and loading speed of 10 mm/min. Split disc fixture, specially adapted to testing machine was used to hold NOL ring samples. For each sample force-deflection diagram was received, where maximal break load was detected.

2.1 Factorial design of experiment

Combination of winding parameters specified in Table 2 has been used in the production of NOL ring samples according to factorial DOE with 2^2 permutations. DOE was used due to it superiority to the traditional one-variable-at a time method, which fails to consider possible interaction between filament winding factors.

Table 2: Combinations of winding parameters using factorial DOE 2^2

N°	X_1 (m/min)	X_2 (N)
1	V_2	F_2
2	V_1	F_2
3	V_2	F_1
4	V_1	F_1

2.2 Taguchi method

Taguchi orthogonal array L_4 is given in Table 3, where parameters affecting the process and their levels are specified. This method was used as a comparative method to DOE, due to its simplicity.

Table 3: Taguchi orthogonal array L_4 (2^2)

N°	X_1 (m/min)	X_2 (N)
1	V_1	F_1
2	V_1	F_2
3	V_2	F_1
4	V_2	F_2

3 RESULTS AND DISCUSSION

Experimental hoop tensile strength (σ_{exp}) of NOL ring samples was calculated according to (1) [7], whereas experimental hoop tensile modulus of elasticity (E_{exp}) of NOL ring samples was determined with help of (2) [8]. Received results are represented in Table 4.

$$\sigma = \frac{F}{2tw} \tag{1}$$

$$E_{exp} = \frac{0.1257 r_{mean}^3}{wt^3} \frac{F}{\Delta} \tag{2}$$

In (1), F (N) is maximal break force of NOL ring sample, whereas t (mm) and w (mm) are the thickness and width of NOL ring sample, respectively. In (2) r_{mean} (mm) is mean radius of manufactured NOL ring sample.

Table 4: Hoop tensile strength and hoop tensile modulus of NOL ring samples according to DOE 2^2

N°	$\sigma_{exp.}$ (MPa)	$\sigma_{exp.med}$ (MPa)	E_{exp} (GPa)	$E_{exp.med}$ (GPa)
1-1	1921.9	1909.6	124.85	129.84
1-2	1869.8		130.17	
1-3	1945.3		132.16	
1-4	1865.8		125.73	
1-5	1945.3		136.29	
2-1	2142.4	2111.5	145.78	144.07
2-2	2123.7		143.58	
2-3	2151.0		149.74	
2-4	2081.5		140.27	
2-5	2059.0		141.02	
3-1	1815.8	1907.3	127.24	134.81
3-2	1949.9		133.54	
3-3	1877.8		128.19	
3-4	1967.3		141.08	
3-5	1925.6		144.00	
4-1	2067.2	2058.0	136.87	139.61
4-2	1957.6		131.07	
4-3	2133.1		144.67	
4-4	2129.6		148.73	
4-5	2002.5		136.70	

3.1 Factorial design of experiment

From results shown in Table 4, value of hoop tensile strength dispersion (S_σ^2) and minimal value of winding parameters (Δb_i) can be calculated [9]. These values are given in Table 5.

Table 5: Results from factorial DOE 2^2 for hoop tensile strength

N°	σ_{exp}	σ_{cal}	S_σ^2	Δb_i
1	1909.62	1908.45	1550.69	26.90
2	2111.52	2084.76	1580.04	
3	1907.28	1908.45	3748.04	
4	2058.00	2084.76	6002.91	

From results represented in Table 5 can be noticed that minimal calculated value for parameter's coefficient is 26.90. According to this value, winding speed (x_1) performs an influence on hoop tensile strength of manufactured samples which is specified with (3).

$$\sigma = 1996.6 - 88.15 x_1 \tag{3}$$

Homogeneity of dispersion and adequacy of represented model are expressed through Cochran criteria ($G_{cal} < G_{tab}$) with G_{cal} equal to 0.466 and Fisher criteria ($F_{cal} < F_{tab}$) with F_{cal} equal to 0.22, respectively.

Table 6: Results from factorial DOE 2^2 for hoop tensile modulus of elasticity

N°	E_{exp}	E_{cal}	S_E^2	Δb_i
1	129.84	132.33	22.22	2.83
2	144.08	141.84	14.76	
3	134.81	132.33	56.63	
4	139.61	141.84	49.42	

Further, Table 6 presents the experimental and calculated values of hoop tensile modulus of elasticity of NOL ring samples, together with calculated dispersion (S_E^2) and parameter's coefficient (Δb_i). In this case, calculated Δb_i is 2.83. Here also, winding speed (x_1) manifest an influence on hoop tensile modulus of elasticity of NOL ring samples which is given with (4). Cochran criteria ($G_{cal} < G_{tab}$), with G_{cal} equal to 0.396 confirm the homogeneity of dispersion, whereas Fisher criteria ($F_{cal} < F_{tab}$) with F_{cal} equal to 0.31 affirm the adequacy of represented model.

$$E = 137.08 - 4.76x_1 \tag{4}$$

3.2 Taguchi method

According to results given in Table 4, but in correspondence to Taguchi orthogonal array L_4, standard deviation (S), log(S) and signal-to-noise ratio (S/N ratio) were calculated for each NOL ring sample (Table 7). S/N ratio was determined following larger-the-better category with help of (5) [10].

$$S/N_{ratio} = -10\log\sum\left[\frac{1}{y_i^2}\right] \tag{5}$$

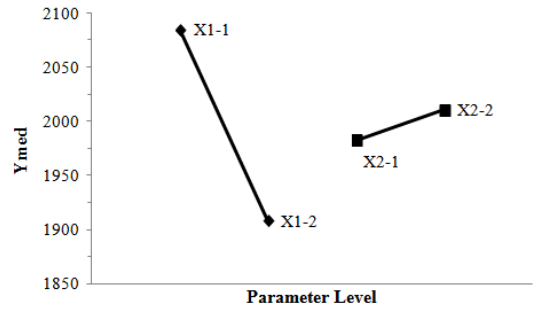
Table 7: Sample statistic according to Taguchi method for NOL ring samples

N°	σ_{exp}			E_{exp}		
	S	log (S)	S/N ratio	S	log (S)	S/N ratio
1	77.5	1.9	66.3	7.0	0.8	42.9
2	39.7	1.6	66.5	3.8	0.6	43.2
3	61.2	1.8	65.6	7.5	0.9	42.6
4	39.4	1.6	65.6	4.7	0.7	42.3

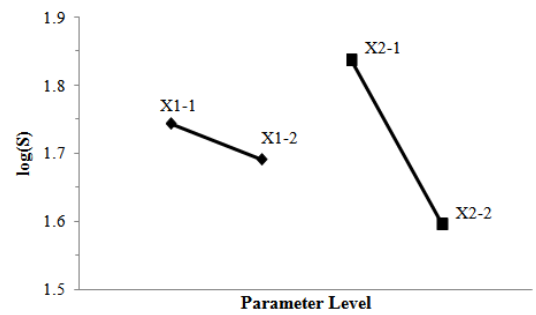
In Fig.1 and Fig. 2 are represented S, log(S) and S/N ratio of calculated σ_{exp} and E_{exp} for each sample. It can be noticed that winding speed (X_1) at level 1 has pronounced influence on mechanical characteristics on standard deviation and S/N ratio, in comparison to winding tension (X_2) which can be negligible. Contrary to this, X_2 has more pronounced influence on log(S) at level 1 for hoop tensile strength and hoop tensile modulus.

Table 8: Rang of parameters according to Taguchi method for NOL ring samples

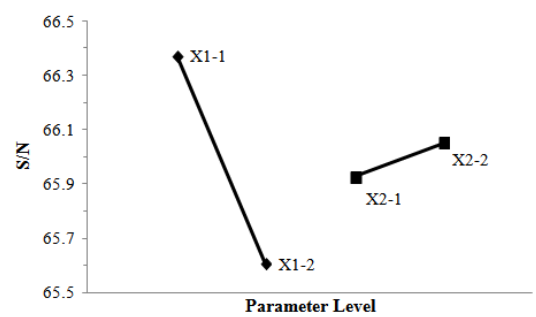
Level	σ_{exp}		E_{exp}	
	X_1	X_2	X_1	X_2
1	66.4	65.6	43.1	42.8
2	65.6	66.1	42.5	42.8
Δ	0.8	-0.5	0.6	0.0
Rank	1	2	1	2



a) Estimated factor effects

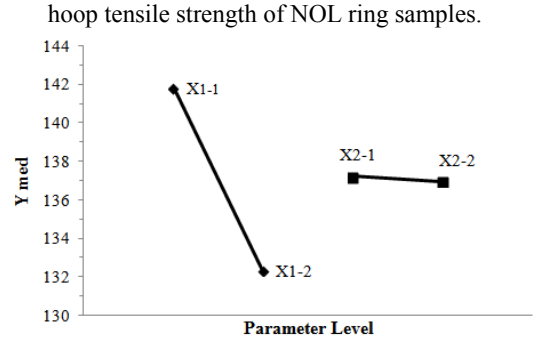


b) Factor effects on log(s)

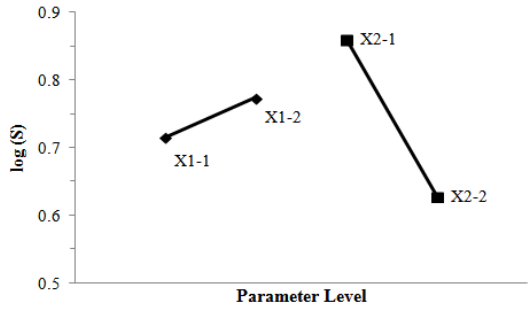


c) Factor effects on S/N ratio

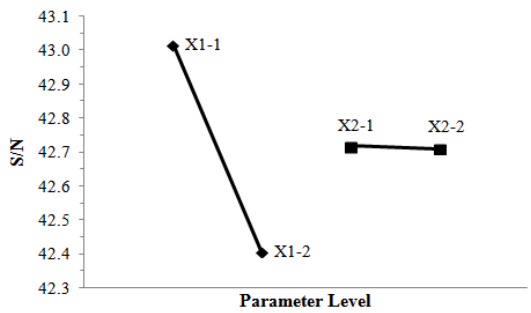
Fig.1: Graphical presentation of factor effects on hoop tensile strength of NOL ring samples.



a) Estimated factor effects



b) Factor effects on log(s)



c) Factor effects on S/N ratio

Fig.2: Graphical presentation of factor effects on hoop tensile modulus of NOL ring samples

4 CONCLUSION

Experimental methods described in this work are suitable to predict the influence of winding parameters on mechanical properties of NOL ring samples manufactured with help of filament winding technology.

Good agreement between both methods was received, where winding speed shows more pronounced influence on mechanical characteristics in comparison to winding tension.

According to factorial DOE interaction between both parameters does not demonstrate an influence on mechanical properties of composite samples, whereas Taguchi method shows that winding speed at level 1 (3.5m/min) demonstrate an effect on mechanical properties of composite samples.

Taguchi method is a structured approach for determining "the best" combination of inputs to produce a product or service. It is based on a Design of Experiments methodology for determining parameter levels and requires small number of experiments. In the same way, DOE is an important tool for designing processes and products. But it is a method which quantitatively identifies the right inputs and parameter levels for making a high quality product or service and requires bigger number of experiments.

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