Archives of Materials Science and Engineering

Volume 28
Issue 3
March 2007
Pages 133-140

International Scientific Journal published monthly as the organ of the Committee of Materials Science of the Polish Academy of Sciences

Application of Taguchi method in the optimisation of filament winding of thermoplastic composites

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Received 15.11.2005; accepted in revised form 10.02.2007

ABSTRACT

Purpose: Purpose of this paper was to find the optimum parameters to produce Twintex® tubes by filament winding.

Design/methodology/approach: Taguchi approach was used for this design. The experiments were done with varying fibers temperature, winding speed, number of layers and roving. Thermoplastic composite rings were manufactured in the thermoplastic filament winding process at selected conditions. The glass and polypropylene fibers (Twintex®) were used to produce tubes. The influence of the main process parameters on tensile strength and also shear strength was assessed.

Findings: As it is presented in this work, the machining parameters, number of layers and roving affect on shear and tensile strength. Fibres temperature is very significant parameter both in tensile strength and shear test.

Research limitations/implications: The main objective of the present study was to apply the Taguchi method to establish the optimal set of control parameters for the tubes by filament winding. The Taguchi method is employed to determine the optimal combination of design parameters, including: fibers temperature, winding speed, number of layers and number of roving.

Originality/value: This paper presents new results of optimisation using Taguchi method filament winding process parameters producing new tubes from the thermoplastic Twintex® material.

Keywords: Filament winding; Thermoplastic composites; Taguchi method's

MATERIALS

1. Introduction

Filament winding is automated process which allows a thermoset resin-impregnated glass reinforcement to be wrapped around a suitable mandrel. The mandrel gives the shape of the final item. A filament winding machine wraps the mandrel with resin-impregnated strands with the required amount and orientation to build the designed reinforced structure. Then the component is cured under high pressure and temperature. Considerable advantages include precise fiber orientations, high fiber to resin ratios, straight untwist fiber path, high consistency and good repeatability can be achieved [3, 5, 8].

This process is primarily used for hollow, generally circular or oval sectioned components. Fiber tows are passed through a resin bath before being wound onto a mandrel in a variety of orientations, controlled by the fiber feeding mechanism, and rate of rotation of the mandrel [3, 9].

Mechanical strength of the filament wound parts not only depends from composition of component material, but also on process parameters like winding angle, fiber tension, resin type and curing cycle. One primary tool used in the filament winding process is a precise ground mandrel on which the fiber with resin matrix is wound. At the end of the filament winding process, the fiber with resin matrix is cured, either at room temperature or in an oven with a controlled heat profile depending on the type and style of the resin matrix used [5].

The filament winding machine was used to produce composite tubes using Twintex® - glass fiber and polypropylene resin matrix. Fibers temperature, winding speed and number of layers and roving are the most frequently used parameters for producing tubes. However, there are large numbers of parameters that can affect the produced tubes. In this paper, Taguchi method was used for optimization of these factors. The Taguchi approach helps in optimization process requiring relatively few experiments.

2. Taguchi method

The Taguchi approach is a form of DOE with special application principles. For most experiments carried out in the industry, the difference between the DOE and Taguchi approach (Fig.1) is in the method of application [10].

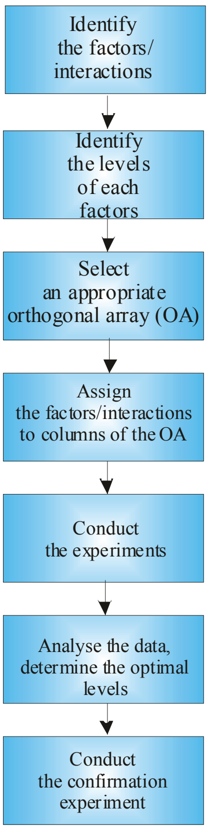


Fig. 1. Scheme of the major steps of implementing the Taguchi method [2]

Taguchi method is a technique for designing and performing experiments to investigate processes where the output depends on many factors (variables, inputs) without having tediously and uneconomically run of the process using all possible combinations of values. Thanks to systematically chosen certain combinations of variables it is possible to separate their individual effects [7].

In Taguchi methodology, the desired design is finalized by selecting the best performance under given conditions.

The tool used in the Taguchi method is the orthogonal array (OA). OA is the matrix of numbers arranged in columns and rows [11]. The Taguchi method employs a generic signal-to-noise (S/N) ratio to quantify the present variation. These S/N ratios are meant to be used as measures of the effect of noise factors on performance characteristics. S/N ratios take into account both amount of variability in the response data and closeness of the average response to target. There are several S/N ratios available depending on type of characteristics: smaller is better, nominal is best (NB) and larger is better [7,12].

3. Experimental procedure

In this work roving composed of commingled glass fibers (GF) and polypropylene (PP) filaments – TWINTEX® R PP (supplied by Saint – Gobain, Vetrotex) were used. The glass weight content is 60% and the nominal lineal weight is 1870 tex. The TWINTEX® supplier gives information for this material that consolidation is done by heating the roving above the melting temperature of PP matrix 180 - 230°C and applying a pressure. Table 1 shows the composite mechanical properties after processing.

Table 1.
Composite mechanical properties after processing

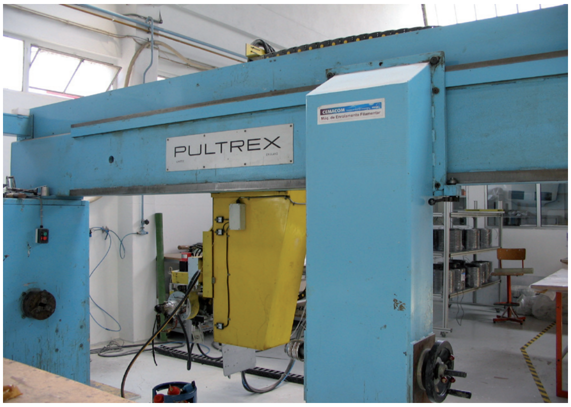
			Undirectional Roving PP 60
Tensile	Strength	MPa	760
	Modulus	GPa	29.5
Flexural	Strength	MPa	740
	Modulus	GPa	25.5

Tubes were produced by filament winding using a CNC conventional PULTREX machine (Fig. 2). Fiber tows were passed through a resin bath before being wound onto a mandrel in a variety of orientations, controlled by the fiber feeding mechanism, and rate of rotation of the mandrel [9].

The semi product was guided with controlled and constant tension, through a tubular pre–heating furnace at the desired temperature. The numerical machine allowed controlling the temperature of heating and fibers temperature, winding speed and angle winding fiber on the mandrel.

Tubular components with an inner diameter of 80 mm and the length of 200 mm were wound. Various fibers temperature, winding speed, number of layers and roving were used in the experiment. The first results show that the fibers temperature and winding speed have influence on the consolidation. When consolidation was poor or if the tube thickness wall was to small was a problem with taking the tube off from the mandrel these condition.

a)



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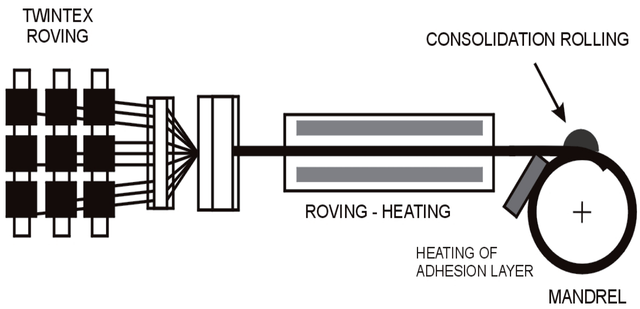

Fig. 2. a) Laboratorial filament winding system, b) Schematic layout [4]

The experimental studies were carried out under varying:

A) fibers temperature,
B) winding speed,
C) number of layers,
D) number of roving.

The machining parameters (winding speed, fibers temperature) and number of layers and roving were determined by using Taguchi experimental design method. A many tubes were made and tests conducted before using Taguchi method to find the best parameters.

In this study, two response parameters: tensile strength and shear test were considered.

3.1. Tensile strength measurements of filament wound ring specimens

One of the most common testing methods (tensile testing) is used to determine the behavior of a sample while an axial stretching load is applied.

Tensile testing was commonly used to determine the maximum load (tensile strength) that a material or a product can withstand [5].

The tensile strength of the tubes was measured using the Instron 4505 machine. The specimen was measured using two different devices. Each tube was cut into three round specimens and each had 6 mm height. Tensile strength was calculated by using the following formula [5]:

$$\sigma = \frac{F_{\max}}{2 \times w \times d} \tag{1}$$

where:
F_{max} – maximum force,
w – ring width,
d – wall thickness.

The tensile strength is an average value from three tests made on each tube.

3.2. Interlaminar shear strength

Shear is the maximum stress sustained before the material will rupture [1].

Shear strength test was carried out using the Instron 4505 universal testing machine (together with data analysis software when more comprehensive testing results are required). Fig.3. shows a diagram of the test set-up. Specimen (10 mm long) was positioned between the shear edges. The testing speed was fixed to 1mm/min.

The shear strength is the maximum shear stress existing between layers of a laminated material.
In case, when the consolidation between fibers and matrix or if the fiber agglomerations is poor, the shear strength will drop. It will happen because load transfer cannot occur fully.

The interlaminar shear strength is indicative of the composite loading capacity along the weakest direction: between the strong composite plies. For instance, damage due to load introduction, impacts, stress concentrations etc. often initiates shear between plies.

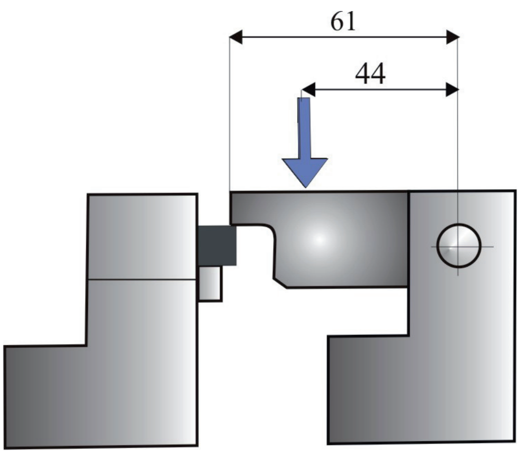

Fig. 3. Schematic view of interlaminar shear test

The shear test was calculated from effective shear force F* divided by the shear area A_{shear} [5]:

$$\tau = \frac{F^*}{A_{shear}} = \frac{\left(\left(\frac{l_k}{l_s}\right) \times F\right)}{w \times h} \quad (2)$$

where:
l_k, l_s – the levers of the test device,
F – the maximum applied test load,
w –sample width,
h –sample height.

Shear test of TWINTEX® composites specimens cut from the consolidated rings were performed. Values determined by the shear strength represent the average value of three specimens from each of tube.

3.3. Experimental design

The experiment using Taguchi method was considered twice. First, to use results from tensile strength and the second time to used results from the shear test.

Table 2 shows four factors and three levels used in the experiment. If three levels were assigned to each of these factors and a factorial experimental design was employed using each of these values, number of permutations would be 3^4. The fractional factorial design reduced the number of experiments to nine. The orthogonal array of L9 type was used and is represented in Table 3. This design requires nine experiments with four parameters at three levels of each. The interactions were neglected. The strength of the part should be maximized [6, 12-15].

Table 2.
Level of process parameters

		Level		
Symbol	Factor	1	2	3
A	Fibers temperature [°C]	210	230	190
B	Winding speed [m/min]	7	10	13
C	Number of layers	4	5	6
D	Number of roving	4	6	8

Table 3.
Taguchi´s L_9 (3^4) orthogonal array

Standard	Factor			
order	A	B	C	D
1	210	7	4	4
2	210	10	5	6
3	210	13	6	8
4	230	7	5	8
5	230	10	6	4
6	230	13	4	6
7	190	7	6	6
8	190	10	4	8
9	190	13	5	4

4. Results and discussion

4.1. Results of tensile strength

Nine different tubes experiments were performed using the design parameter combinations in the specified orthogonal array table. Three specimens were fabricated for each of the parameter combinations. The completed response table for these data appears in Table 4. In order to estimate the effect of factor A (fibers temperature) on the average value of response variable, were summed together three observed response at level 1 of factor A. Then the sum was divided by 3 to obtain the average response at level of factor A. The average responses at level 2 and 3 was obtained in the similar manner. The estimated effects are presented graphically in Fig. 4. The range of average responses at the bottom Table 4, over the three levels of each experimental factor, is:

- for fibers temperature = 73.4,
- for winding speed = 21.3,
- for number of layers = 91.77,
- for number of roving = 43.167.

In particular, factor A (fibers temperature) and factors C (number of layers) should be set at level 2 (230°C) for factor A (fibers temperature) and 1 (4 layers) for factor C (maximized tensile strength).

The sample standard deviation is generally accepted measure of variability in statistical data analysis and experimental design. This statistic is somewhat more difficult to calculate than the sample range, but it has desirable properties which make its use worth the added effort [7, 16].

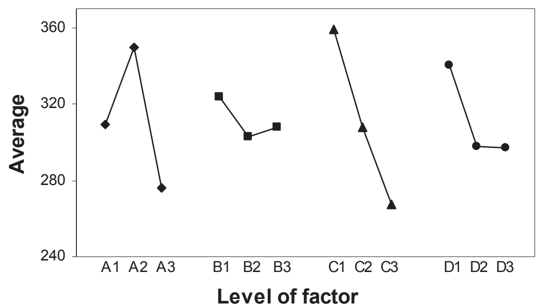

Fig. 4. Estimated factor effects

The standard deviation was calculated for each tube in five steps. First, $\bar{y}$ was subtracted from each measurement in the sample (sample mean), then the square differences obtained prior were calculated. Next, the squared obtained differences were and was divide the sum by the sample size minus one (s^2). Finally obtain the square root of s^2.
The sample variance is written as formula [3]:

$$s^2 = \sum \left(y - \bar{y}\right)^2 / (n-1) \quad (3)$$

$$s = \sqrt{s^2} \quad (4)$$

Table 4.
Experimental data and sample statistics

Experiment number	Observed response values for tensile strength [N/mm^2]			Mean	Standard deviation	Logarithm of standard deviation	S/N Ratio
1	394.77	395.45	403.34	397.85	4.75	0.67	51.99
2	268.75	282.84	297.03	282.87	14.14	1.15	49.01
3	245.29	243.80	251.11	246.73	3.81	0.58	47.84
4	360.79	285.93	384.61	343.78	51.49	1.71	50.51
5	304.06	323.46	316.89	314.80	9.86	0.99	49.95
6	370.82	359.03	408.92	379.59	29.07	1.41	51.54
7	251.20	218.31	222.73	230.75	17.85	1.25	47.21
8	286.81	285.74	328.65	300.40	24.46	1.38	49.49
9	270.98	281.14	337.83	296.65	36.02	1.55	49.32

The estimated log s effects from Table 4 are plotted in Fig.5. Both factor A and C again affect the tensile strength variability. In order to minimize variability:

- fibers temperature– level 1, (210°C),
- number of layers – level 3, (6 layers) should be used.

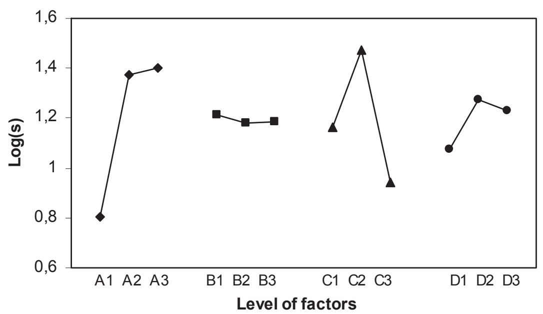

Fig. 5. Estimated factor effects on log(s)

Results:

- factor A, fibers temperature, at level 1,
- factor B, negligible,
- factor C, layers, at level 3,
- factor D, roving, at level 1.

In this work, the larger tensile strength is the indication of better performance [3, 5]. Therefore, the larger-is-better for the tensile strength was selected for obtaining optimum machining performance characteristics. The following S/N ratios for the larger-is-better case could be calculated [5]:

$$S/NRatio = -10\log\left(\sum\left(\frac{1}{y^2}\right)/n\right) \tag{5}$$

For example, average response of B (winding speed) at level 3 was obtained from the results of experiments 3, 6, 9 since level 3 of parameter B was used in these experiments. So, average response for this = S/N Ratio$_3$ + S/N Ratio$_6$ + S/N Ratio$_9$ = 49.57. Similar calculations were performed for the another factors and levels. The average responses for all parameters are given in Table 5 with Overall mean S/N Ratio.

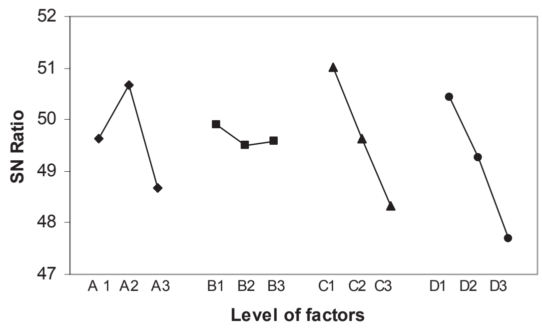

Fig. 6. Plot of factor effects on S/N ratio

Table 5.
Overall mean S/ Ratio

Level	Average S/N Ratio by factor level				Overall mean S/N Ratio
	A	B	C	D	T
1	49.62	49.91	51.01	50.43	49.52
2	50.67	49.49	49.62	49.26	
3	48.68	49.57	48.34	47.69	

In order to maximize the S/N ratio, the following assignments were done: factor A (fibers temperature) - level 2, factor B (winding speed) - negligible, factor C (layers) - level 1, factor D (roving) - level 1.

Figure 6 indicates that factor C and D have a strong effect on average S/N ratio response. Factor A is the next most significant. The above analyses of Table 4 and Table 5 are summarized in Table 6. In that table the levels of key factors which are optimizing the response are listed. Some significant levels are shown on Fig. 4, 5, 6. Keep in mind that the objective is to maximize the response average, reduce log s, and maximize the S/N Ratio.

There are two ´´conflicts´´ in the levels recommended in Table 6. For factor A (fibers temperature), level 2 for maximize average and maximize the S/N Ratio, but level 1 for minimize log s. In this case, however, the reduction in log s does not appear to be significant, but the average and S/N Ratio do appear to be relatively large. For factor C-layers, the situation is similar to case in factor A (level 1 for average and S/N Ratio, and level 3 for response logs).

Table 6.
Summary of analyses of factor effects

	Level which was optimized		
Factor	$\bar{y}$	log s	S/N Ratio
A	2	1	2
B	1		
C	1	3	1
D	1		

In this range: 7-10 [m/min] the winding speed is not very significant.

In this study factors A and C were two dominant. These final optimized parameter values are:
- fibers temperature , level 2 - 230°C,
- winding speed, level 1 - 7[m/min],
- number of layers, level 1 - 4 layers,
- number of roving, level 1 - 4 roving.

4.2. Results of shear test

The experiment was performed using the results from shear strength test. The column in the design matrix (to which factors were assigned) and the experimental levels for the factors, are the same as in the case design for a tensile strength test.

The values for tubes 5 and 9 are equal 0. Specimens preparation from these tubes was impossible, the consolidation of these two tubes was bad.

The factors combination which used the observed values for the response and calculated values for $\bar{y}$, s and log s are listed in Table 7.

Fig. 7 shows that the main effect had factors A (fibers temperature) and D (number of roving). The factors B (winding speed) and C (number of layers) appear to be random variability.

The range of average responses at the bottom of Table 7 over the three levels of each experimental factor was:
- for fibers temperature, range = 10.73,
- winding speed, range = 5.45,
- number of layers, range =2.28,
- number of roving, range = 11.25.

The ranges change the average shear test as winding speed or layers are less than the range fibers temperature or roving. Conclude changes in winding speed or number of layers do not have a significant effect on the average tensile shear. However, the fibers temperature and number of roving have strong effect on tensile shear. Maximize variability fibers temperature – level 1 (210°C). Shear strength is much lower when roving is 4. The other two levels would be preferred, since the order to maximize shear test is required (Fig. 7).

If the ranges of average values for log s were calculated over three levels of each experimental factor, following results was obtained (Fig.8):
- fibers temperature, range = 0.15,
- winding speed, range = 0.3,
- number of layers, range = 0.5,
- number of roving, range =0.38.

Factor C (number of layers) affects variability the most. Factors D (number of roving), B (winding speed), A (fibers temperature) are not so important.

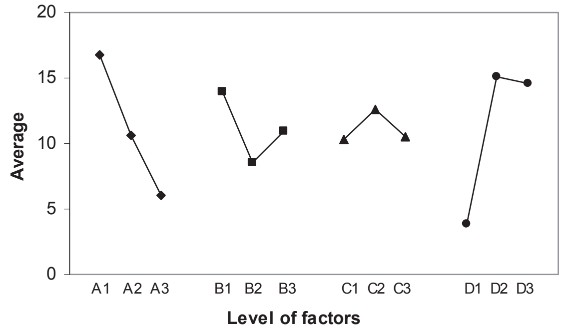

Fig. 7. Plot of factor effects on average

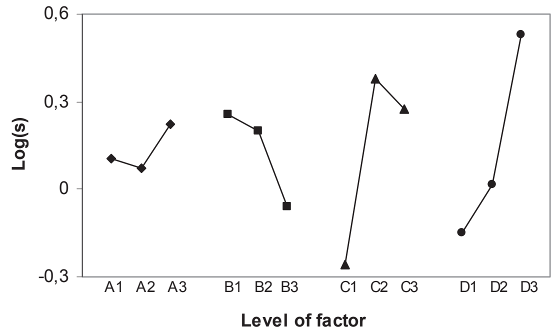

Fig. 8. Plot of factor effects on log(s)

For S/N ratios, Fig. 9 shows that factor A – fibers temperature and D - roving have a strong effects, and factor B -winding speed is the next (similar in average response). It appeared from the effects calculated at the bottom of Table 7 that in order to maximize the S/N ratio, the following assignments should be made:
- factor A, fibers temperature, at level 1 - 210°C,
- factor B, winding speed, at level 1 – 7 [m/min],
- factor D, number of roving, at level 2 – 6 roving.

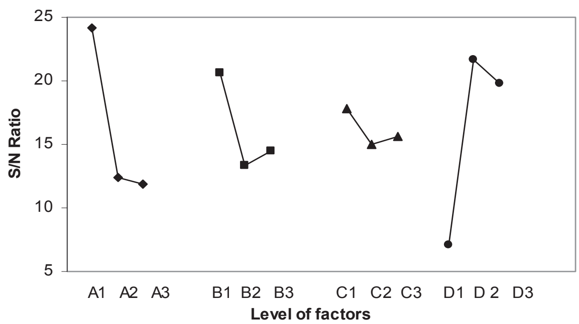

Fig. 9. Plot of factor effects on S/N Ratio

Table 7.
Experimental data and sample statistics

Experiment number	Response values for shear test [N/mm^2]			Mean	Standard deviation	Logarithm of standard deviation	S/N Ratio
1	11.87	11.20	11.30	11.45	0.36	-0.439	21.17
2	21.82	18.44	18.33	19.53	1.98	0.297	25.75
3	17.36	18.18	22.61	19.39	2.82	0.451	25.58
4	15.85	12.94	26.09	18.29	6.90	0.839	19.42
5	0	0	0	0	0	0	0
6	13.30	13.47	13.77	13.51	0.23	-0.627	17.84
7	13.28	9.46	13.78	12.17	2.36	0.373	21.32
8	7.28	7.06	3.75	6.03	1.97	0.296	14.36
9	0	0	0	0	0	0	0

The above analyses were summarized in Table 8. The objective is to maximize the response average, reducing log s, and maximizing the S/N ratio. There is only one "conflict". For factor B (winding speed) level 1 maximizes the average and S/N ratio, but level 2 minimizes log s. In this case, the reduction in log s does not appear to be significant, but the reductions in $\bar{y}$ and S/N ratio do appear to be relatively large. The effect on log s may be simply random variability rather than a real effect. Factor C is negligible in this case.

Table 8.
Summary of analyses of factor effects

	Level which was optimized		
Factor	$\bar{y}$	log s	S/N Ratio
A	1		1
B	1	2	1
C		1	
D	2	2	2

These final optimized parameter values are:
- fibers temperature , level 1 (210°C) ,
- winding speed, level 1 -7[m/min],
- layers, level 1 - 4 layers,
- roving, level 2 - 6 roving.

5. Conclusions

For the experimental design of thermoplastic filament winding process was applied Taguchi approach. Uses a special design of orthogonal arrays, only nine experiments were needed to determine the optimum condition for the filament winding process.

The experiment conducted with the Taguchi method has demonstrated that the fibres temperature is very important. Fibres temperature is significant both in tensile strength and shear test. The most adwantageous for the tensile strength is temperature 230°C, for shear test 210°C. The temperature of 190°C probably is to low, because the consolidation in this temperature is weak, and in this case, the result is unacceptable.

In this experiment, speed winding range between 7-10 m/min has not significant influence on the tensile strength; however the optimum speed winding is 7m/min.

Changes of the numbers of roving do not have a significant effect on the tensile strength, whereas numbers of layers do not have effect on the shear test.

Acknowledgements

Investigations were partially carried out within the framework of the Socrates Erasmus programme in INEGI – Institute of Mechanical Engineering and Industrial Management in Portugal.

Additional information

The presentation connected with the subject matter of the paper was presented by the authors during the 11th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAM3S'2005 in Gliwice-Zakopane, Poland on 6th-9th December 2005.

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