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Research Article

Designing Technological Process for Composite Pipe Production Using Software

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Abstract

This article uses Statgraphics Centurion software to design filament winding technology for creating composite pipes. The process involves three key parameters: speed of extraction, fiber tension, winding angle, and stretching strength. The software allows for more control over experiments and data filtering. Tables and graphs are created to display the statistical model. A regression equation is obtained to describe the process. The winding angle has the greatest influence on the strength of composite pipes, with larger angles leading to higher tensile strength. Fiber tension and winding speed have minimal influence on the tensile strength of the samples. The software also provides more control over experiments and data filtering.

Keywords: filament winding technology; experiments; parameters; design; tensile strength

Introduction

Solving many engineering problems often involves performing complex and expensive experiments. Hence, the significance of the existence of ways and methods for optimal planning of experiments, which in several cases allow to significantly shorten the time and material costs when performing the research, is understandable [1]. The development of many technologies, which enable our modern way of life, is closely related to the development and availability of certain materials. Computer-aided design is a standard part of the training of today's engineer, who has at his disposal the widely available packages for modelling, optimization, and selection of materials and processes. The software package for the selection of materials and processes relies on a database of attributes of materials and processes and their mutual compatibility, which allows the search and selection of those materials and processes that best meet the requirements of an appropriate design.[2]

Mathematical Methods for Optimal Planning of Experiments

Files Beginning in the early 20th century, the English mathematician Ronald Fisher (Roland A. Fisher) made the first attempts to apply mathematical methods for the best experiment planning. The theory of design of experiments began to develop particularly rapidly after 1951 and is associated with the work of George Box and Kenneth Geddes Wilson. The methods of optimal planning of the experiments allow the use of mathematical methods not only for processing the results of the tests but also in the phase of preparation and implementation of the experiments. The work of researchers using those methods is greatly facilitated because it is carried out according to a logically defined sequential procedure. [1-3]

In modern mathematical theory for optimal planning of experiments, there are two basic departments:

1. Planning experiments to study the mechanisms of complex processes and the properties of multi-component systems.

2. Planning experiments for optimization of technological

processes and properties of multi-component systems. [4]

3. The methods and ways of performing the experiments should allow us to obtain the maximum amount of information with the minimum number of trials. The plan of the experiment is closely related to the study of the process or system for which we perform the experiment, i.e., gaining knowledge about them. [1,5,2]

Factorial Design of Experiments

Many experiments involve studying the effects of two or more factors. In general, factorial designs are the most efficient for this type of experiment. By factorial design, we mean that in one complete experiment, all possible combinations of the factors are investigated. For example, if we have a factor level X1 and X2, the complete experiment will contain all ab combinations. When factors are ordered in a factorial design, they are often said to be crossed. [6,7] The change in response that results from a change in a factor's level is what we refer to as the factor's effect. This is often called the main effect because it refers to the primary factors of interest in the experiment. In some experiments, it may be observed that the response difference between levels of one factor is not the same at all levels of the other factor. If this is the case, it means that there is an interaction between the factors. [8]

Filament Winding Technology

Filament Winding Technology is a process used to manufacture composite structures such as pipes for transporting fluids and gases, tanks for liquid petroleum gas, compressed natural gas, electrical insulators, lamp posts, windmills, and other products. Filament winding technology is one of the most used techniques for obtaining polymer composite materials. To produce composite materials with this technology, a reinforcing material is used in the form of continuous fibres (mostly glass, carbon, or aramid), which are impregnated with a polymer thermoreactive matrix in the form of a liquid resin (polyester, epoxy, etc.) and wound on a rotating mandrel. This technology is performed on specially designed machines, which allow precise control of the winding angles when winding the fibers. The structures can be ordinary cylinders or tubes with different diameters and lengths. Spherical, conical, and other shapes can also be wound. [9-15]

The entire production process of winding composites consists of the following systems:

1. Resin system preparation unit
2. A station where the fibres are unwound, and the tension is controlled
3. Resin bath
4. Impregnation tub
5. The pay-out eye and thread transport system
6. Mandrel

This fiber winding technology is schematically presented in Fig. 1.

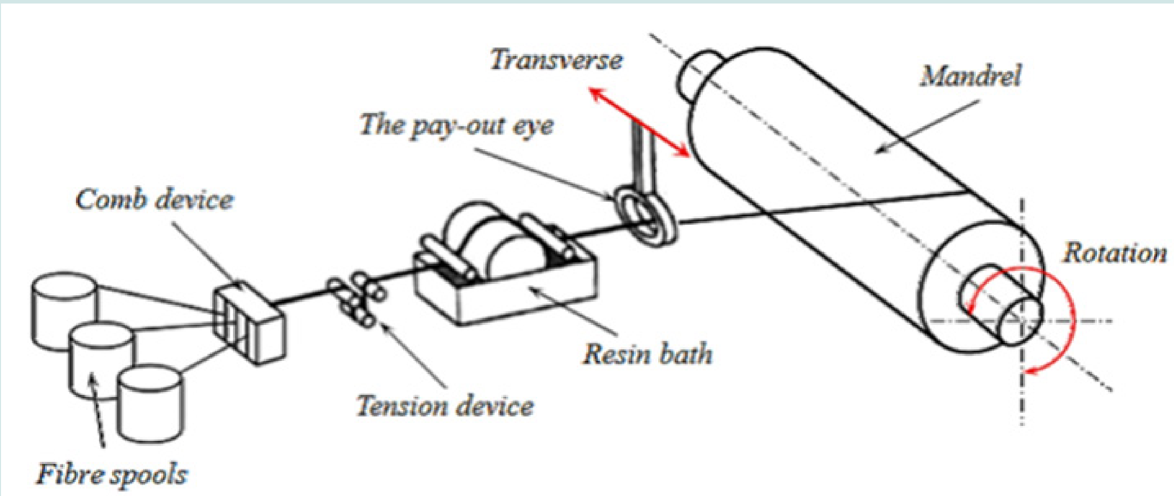

Figure 1: Styles and sizes for equations.

Experimental Part

During the experimental tests, glass fibers and thermoreactive epoxy resin were used as reinforcements for making composite pipes. A three-component epoxy system from Huntsman was used in this research: Araldite LY1135-1/Aradur 917/Accelerator 960-1. The hardener is anhydride, while the catalyst is an amine. The Araldite LY1135-1/Aradur 917/Accelerator 910 resin system is a mix of epoxy resin, anhydride hardener, and amine catalyst. This resin system is intended for the production of high-performance composite parts. Processes in which it is recommended to use are filament winding technology, pultrusion, and pressure moulding technology. Table 1 lists the component characteristics of the Araldite LY1135-1/Aradur 917/Accelerator 960-1 resin system. The Statgraphics Centurion software program was used to plan the experiments, which solves the problem, and the program also allows additional control over the experiment and data filtration. This program contains several procedures for the design and analysis of many different types of experiments. These procedures allow the engineer to create a set of experimental functions that will provide the maximum amount of process information with the least number of trials or experiments. The Statgraphics program allows us to describe and analyze designs to identify the most important factors.By applying the techniques of Response Surface and Multilevel Factorial in Statgraphics software, the results of the designed experiment were analyzed. In designing the process, three parameters that affect the experiments the most are taken: drawing speed, fiber tension, and winding angle, and the tensile strength is taken as a response. Based on the entered data for the selected factors and the obtained values for the response function (tensile strength), a series of tables and 2D and 3D graphs were created to display the statistical model.

Table 1: The characteristics of the components of the resin system.

Araldite® LY 1135-1		
Aspect (visual)	clear, pale yellow liquid	
Colour (Gardner, ISO 4630)	≤ 2	
Epoxy content (ISO 3000)	5.30 - 5.45	[eq/kg]
Viscosity at 25 °C (ISO 12058-1)	10000 - 12000	[mPa s]
Density at 25 °C (ISO 1675)	1.15 - 1.20	[g/cm^3]
Flash point (ISO 2719)	> 200	[°C]
Aradur® 917		
Aspect (visual)	clear liquid	
Colour (Gardner, ISO 4630)	≤ 2	
Viscosity at 25 °C (ISO 12058-1)	50 - 100	[mPa s]
Density at 25 °C (ISO 1675)	1.20 - 1.25	[g/cm^3]
Flash point (ISO 2719)	195	[°C]
Accelerator 960-1		
Aspect (visual)	light yellow liquid	
Colour (Gardner, ISO 4630)	≤ 8	
Viscosity at 25 °C (ISO 12058-1)	150 - 300	[mPa s]
Density at 25 °C (ISO 1675)	0.95 - 0.97	[g/cm^3]
Flash point (ISO 2719)	110 - 120	[°C]
Storage temperature (see expiry date on original container)	2 - 40 °C	[°C]

Results

Table 2 shows the calculated effects of the response function (y) and the interactions between them. Also shown is the standard error of each effect. It should be noted that the largest variance in variance factor (VIF) is equal to 1. For a perfectly orthogonal design, all factors (VIF) should be 1. Factors of 10 or greater are interpreted as severe interference between effects. From the displayed bar graph in Figure 2 as well as from the data in Table 2, it can be concluded that the winding angle has the greatest effect on y, and the effects of the other two factors, winding speed and fiber tension, are much smaller. It is also observed that there are interactions between the factors that have a much smaller effect on y than the winding angle. Figure 3 shows the effects of the factors individually, and Figure 4 shows the interaction of the factors. Table 3, obtained from the software program, shows the results of the calculations for the variation of u. The level of significance is usually taken as 0.05 in calculations, which means that we allow only 5% error in our calculations or consider that the obtained results are calculated with 95% accuracy. That is why it is necessary to calculate values for R to be less than 0.05. According to the obtained values for P, only one effect (winding angle) has a value of less than 0.05. Then, the software program allows the calculation of the coefficients for the regression equation of the model (table 4) and gives the regression equation itself.

Table 2: Calculated effects for y (response function).

Effect	(Estimate) Calculated	(Stnd. Error) Standard error	VIF-Variance of the variation factor
Medium average	411,659	12.81	
A: Speed	50,55	25.62	1
B: Tension	5.85	25.62	1
C: Angle	782,545	25.62	1
AB	-24.1225	25.62	1
AC	49.0025	25.62	1
BC	-0.9725	25.62	1

Table 3: Results of the calculations of variation for y (function response).

Source	(Sum of Squares) A set of squares	Df	(Mean Square) Middle square	F-ratio	P-value
A: Speed	5110.6	1	5110.6	3.89	0.2986
B: Tension	68,445	1	68,445	0.05	0.8571
C: Angle	1.22E+06	1	1.22E+06	932.95	0.0208
AB	1163.79	1	1163.79	0.89	0.5192
AC	4802.49	1	4802.49	3.66	0.3067
BC	1.89151	1	1.89151	0	0.9758
Total error	1312.77	1	1312.77		
Total (cor.)	1.24E+06	7			

Table 4: Regression coefficients for y (the response of the function).

Coefficient	Calculated value
constant	-157,914
A: Speed (X1)	5.11383
B: Tension (X2)	1.0276
C:Agol (X3)	8.80691
AB (X1X2)	-0.0665908
AC (X1X3)	0.0777817
BC (X2X3)	-0.00052853

The equation of the corresponding model is:

$$y = -157{,}914 + 5{,}11383\, x_1 + 1{,}0276\, x_2 + 8{,}80691\, x_3 - 0{,}0665798\, x_1 x_2 + 0{,}0777817\, x_1 x_3 - 0{,}000528233\, x_2 x_3 \quad (1)$$

where the variable values are listed in their original unit (model r in engineering units). It can be noted that the coefficient before factor x3 has the highest value, which indicates its greatest impact on the response, i.e., the tensile strength. The software-derived plan matrix with coded factors is given in (Table 5, 6) contains information about y values generated using the modeled model. The table gives values for:

Table 5: Correlation matrix for predicted effects.

		(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1)	average	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
(2)	A: Speed	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
(3)	B: Tension	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
(4)	C:Agol	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
(5)	AB	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
(6)	AC	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
(7)	BC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

Table 6: Predicted results for y (the response function).

Order	(Observed) Results obtained for u	(Fitted) Calculated values for y (function response)	(Lower 95.0% CL mean) Mean values with accuracy lower than 95.0% CL	(Upper 95.0% CL Mean) Mean values with accuracy greater than 95.0% CL
1	25,32	12.51	-418.13	443.15
2	875.14	862.33	431.69	1292.97
3	22,275	35,085	-395,555	465,725
4	780,465	767,655	337,015	1198.29
5	725,845	738,655	308,015	1169.29
6	16.95	4.14	-426.5	434.78
7	17.0	29.81	-400.83	460.45
8	830,275	843,085	412,445	1273.72

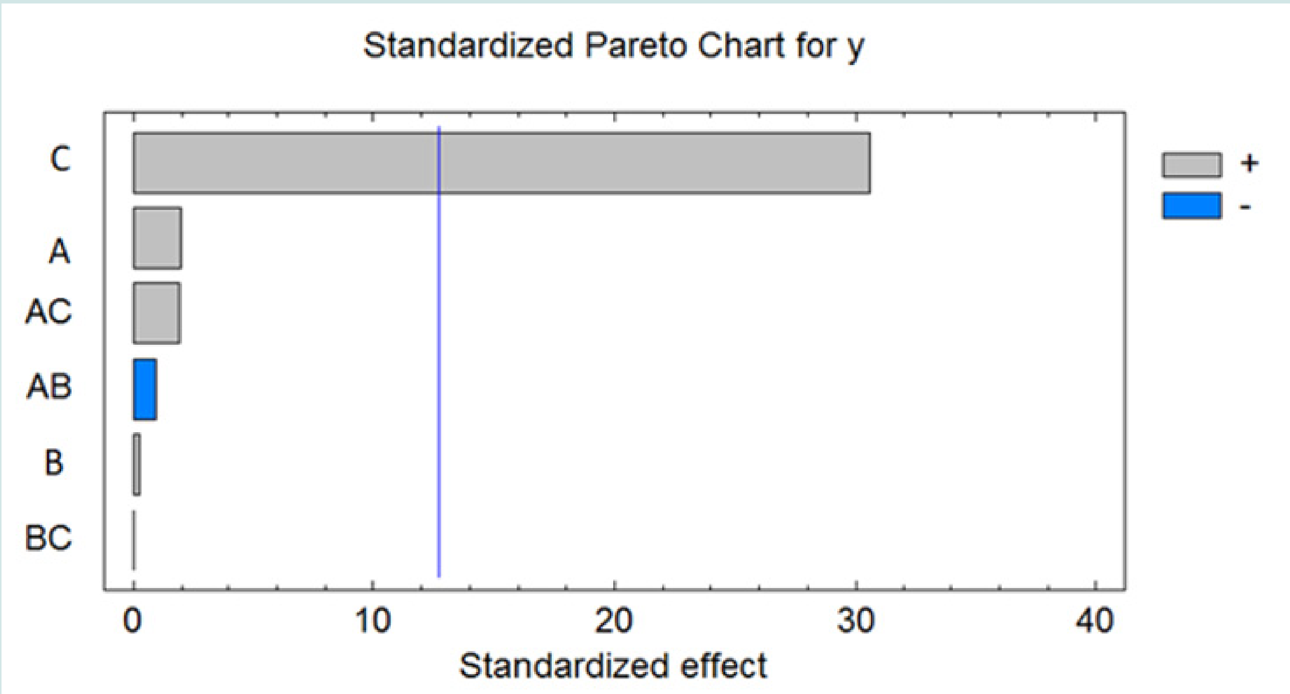

Figure 2: Display of the effect of process parameters and their interaction on y (response function, tensile strength).

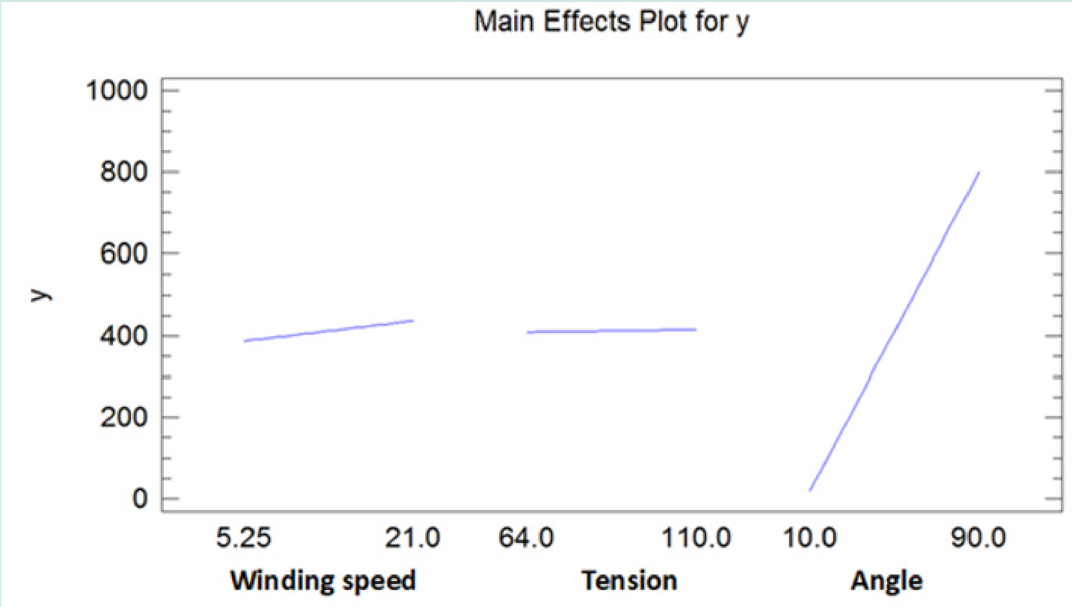

Figure 3: Influence of process parameters on y (function response).

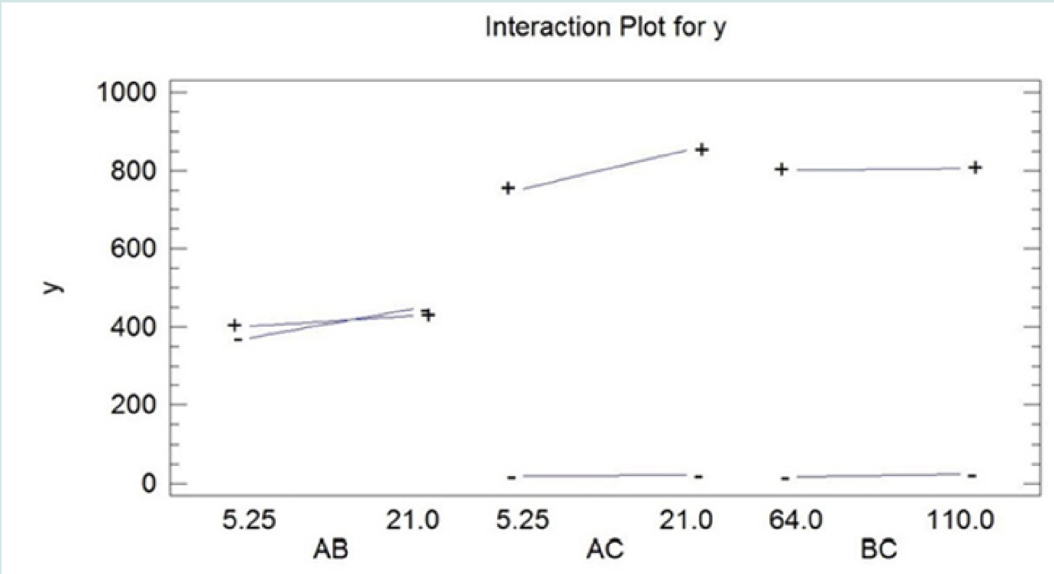

Figure 4: Interaction of factors and effects on y (function response).

1. obtained experimental values for y (function response),

2. predicted (calculated) values for y (function response) using a simulated model,

3. 95.0% significance limit (significance level) for the response mean.

From the tables and analyses made with the software package, it can be concluded that optimal results are obtained for a winding angle value of 500 and 550. That is, the tensile strength mostly depends on the winding angle. Optimum strength values are obtained for an angle of 550, a filament tension of 87 and a winding speed of 14. The created graphical representation given in Figures 5. and 6 gives the effect of variables: winding speed and fiber tension at winding angles of 500 and 550 respectively.

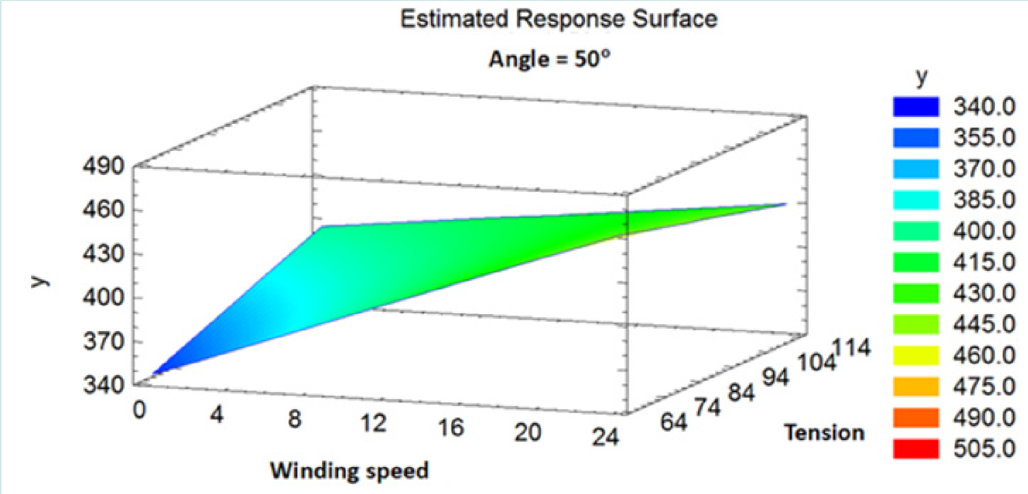

Figure 5: 3D graphical representation of the effect of variables: winding speed and fiber tension at a winding angle of 500.

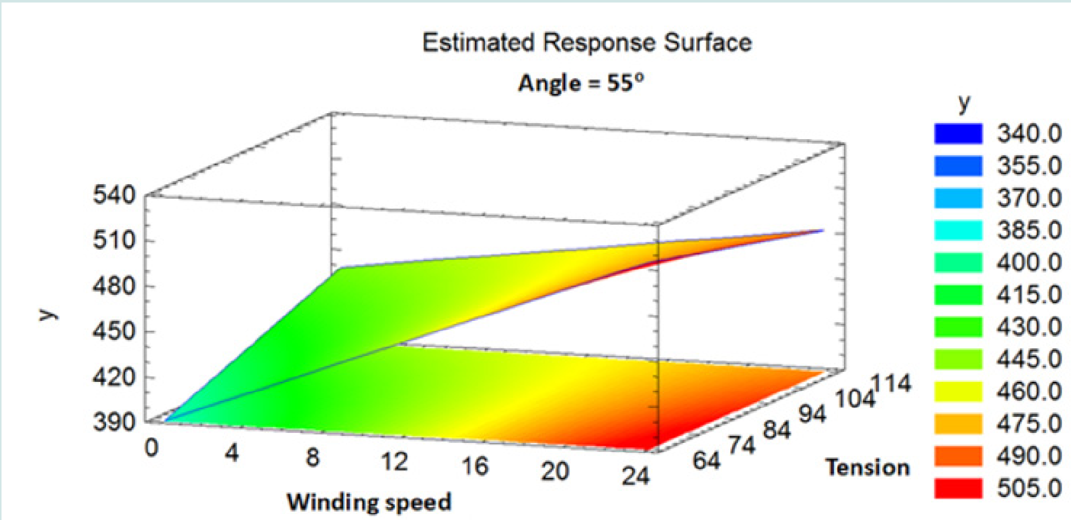

Figure 6: 3D graphical representation of the effect of variables: winding speed and fiber tension at a winding angle of 550.

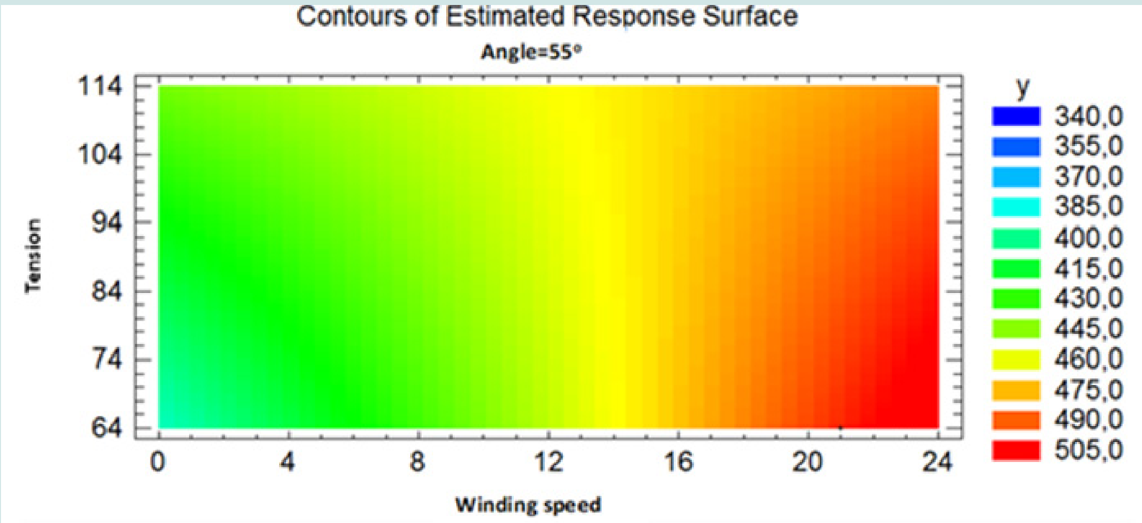

Figure 7: Contours of the predicted response surface at an angle of 550.

Conclusion

Through the design of the technological process to produce composite pipes, it was shown the importance of the existence of ways and methods for optimal planning of experiments, which allow for significantly reducing the time and material costs during the execution of the research. The application of methods for planning experiments allows for solving many problems in chemical technology as well as in other branches of engineering that are related to performing complex and expensive experiments. With filament winding technology, it is possible to produce a final product, mostly to produce cylindrical and spherical shapes, i.e., it is used to produce tanks and tankers for chemicals and fuel, as well as to produce pipes. Tubes obtained by the fiber winding process are a good substitute for corrosive steel and metal pipes for oil, gas, and water. In addition, the pipes obtained by this process are durable, even at high pressures.

Author's Contributions

SaraSrebrenkoska: Drafted and wrote the manuscript and performed the experiment and result analysis. Dejan Krstev: Supervised the experiment's progress and helped in manuscript preparation. Sasko Dimitrov: Assisted in analytical analysis and designed the experimental part. Aleksandra Risteska-Kamceski: Assisted in experimental analysis and helped in manuscript preparation.

References

1. Спирин Н, Лавров В (2004) Методи планированија и обработки резултатов инженерного експеримента. ГОУ ВПО УГТУ УПИ Екатеринбург.
2. Новик ФС, Арсов ЯБ (1980) Оптимизация процессов технологии металлов методами планирования экспериментов. Москва Машиностроение.
3. Семонов СА (2005) Планирование експеримента в химии и хемическој технологии. Москва.
4. Goupy J, Creighton L (2007) Introduction to Design of Experiments. SAS Publishing.
5. Риков В, Иткин В (2008) Математическаја статистика и планирование експерименатa, РГУ нефти и газа им. ИМ Губкина.
6. Ruxton G, Colegrave N (2013) Experimental Design for the Life Science. Oxford University Press.
7. Dean A, Voss D (1999) Design and Analysis of Experiments. Springer Verlag New York.
8. Димески Д, Сребренкоска В (2014) Дизајн и анализа на експерименти. Универзитет Гоце Делчев Штип.
9. Sobrinhoa LL, Caladob VM, Bastian FL (2011) Development and Characterization of Composite Materials for Production of Composite Risers by Filament Winding. Materials Research 14(3): 287-298.
10. Stanley T, Peters, YuM Tarnopol'skii, Beil AI (1998) "Handbook of Composites" Chapter - Filament Winding 456-475.
11. Агајинц И, Орлов А (1998). Планирование експеримента и анализ данних. МИТХТ.
12. Akkus N, Genc G, Girgin C (2008) Control of the presentation in Filament winding process. Acta mechanica et automatica 2(3).
13. Cohen D (1997) Influence of filament winding parameters on composite vessel quality and strength. Elsevier Science Limited 28(12): 1035-1047.
14. Ma Quanjin, Rejab MRM, Kumar NM, Idris MS (2008) Experimental assessment of the 3-axis filament winding machine performance.
15. Huntsman (last access: 11.10.2023).

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