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SIX SIGMA AND DESIGN OF EXPERIMENTS FOR IMPROVING THE PRODUCTION OF COMPOSITE PIPES

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ABSTRACT

Within the frames of this paper it was applied the six-sigma DMAIC methodology for improving the production process of composite pipes. The quality needs of the composite pipes were defined: resistance on high interior pressure and the important entries that influence on the improved solution. A designing was made for improving of the industrial process, i.e. planning of the experiments and on the basis of the plan matrix, 8 models of composite pipes were manufactured. During the process of designing three parameters were taken which influence the experiments the most: velocity, fiber tension and winding angle. Also, it was used three-factorial method for experimental planning with two levels of variation 2^3. For all manufactured composite pipes the hoop tensile strength was tested in a lab. On the basis of the received experimental data it was created the regression equitation which the best describes the process.
Key words: *six sigma, experimental design, plan matrix, fiber winding, composite pipes, tensile strength.*

1. INTRODUCTION

More and more factors have an influence on effectiveness and efficiency in the industrial processes and systems. An important question of science is to identify the most important factors for controling complex processes and systems, to know their levels and influences to control all things in a right manner.

Six Sigma is a methodology for eliminating defects. This is an important task in industrial processes. But Six Sigma is also a philosophy to work and a business strategy too. The goal is to achieve a process level in standard deviations six sigma. After Motorola in the 1980s were published a lot of success stories as in manufacturing, in different services, in research, in healthcare

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and e.g. in government too. The list of enterprises which adapt six Sigma is important e.g. Xerox, Boeing, GE, Kodak, Sony, Polaroid, NASA, Dupont, Toshiba, Ford, ABB. The original terminology "Six Sigma" is based on the established statistical approach. This is described by a sigma measurement scale. The range is normally from one / two to six sigma. It defines how much of a product or process normal distribution is contained inside the specification. Essentially, the higher the sigma value the less is the defect rate, because the process distribution is contained inside the specification.

There have evolved two key methods for carrying out Six Sigma. The first method is the most well-defined and works best if you have a problem with an unknown solution in existing products, processes or services. This method is called DMAIC:

- Define - improvement of project goals, goals based on customer needs and wants.
- Measure - current process and establish metrics to monitor the path to achievement of goals.
- Analyze - current process to understand problems and their causes.
- Improve - process by identifying and piloting solutions to problems.
- Control - improved process with.standardization and ongoing monitoring.

Each of these processes (phases) can be realized with different tools and techniques while some tools can be used in more than one processes (phases). One possible use of technique in the Six Sigma methodology for an improvement process is design of experiments (DoE).

The newest method, which is in the developing stages, is called Design for Six Sigma or DFSS. The goal of DFSS is to develop a new product, process or service that is defect-free in the eyes of the customer.

To find the optimum in control there are often a lot of experiments to realize – practical and theoretical ones. In this field the sensitivity analysis as well as simulation and the design of experiments too are used. This is necessary to rapidly prevent failures and solve problems early. Design of experiments has an old tradition and history by R. Fisher, Taguchi, Shainin i.e. design of experiments is a structured, an established and an organized method of quality management. The key factor to minimize optimisation costs is to realize as few experiments as possible. Design of experiments requires only a small set of experiments and thus helps to reduce costs. Design of experiments is used to determine the relationship between the different factors (xi) affecting a process and the output (result) of that process (y). Design of experiments has more to offer than a "one change at a time experimental method". "One change at a time experimental method" has always the risk that the researcher will find only the significant effect on the output. Design of experiments also focuses on dependency and interaction between the factors. Design of experiments plans for all possible dependencies at first, and then prescribes exactly which data are needed to assess them. The exact length and size of the experiment are set by the experimental design before the real experiments begin.

Design of Experiments involves designing a set of experiments, in which all relevant factors are varied systematically (Fig. 1). When the results of these experiments are analysed, they help to identify optimal conditions. Further results of design of experiments are:

- The factors that most influence the results (high effect).
- The factors that little influence the results (small effect).
- The existence of interactions and synergies between factors.

The common way to use design of experiments is the following:

- Define the objective of the investigation.
- Define the variables (factors) *yk* that will be measured to describe the output.
- Define the variables (factors) that will be controlled xi during the experiment.

- Define the ranges of variation and the factor levels of each factor.
- Define and optimise the experimental plan.
- Prepare and carry out the experiments carefully and secure the results.

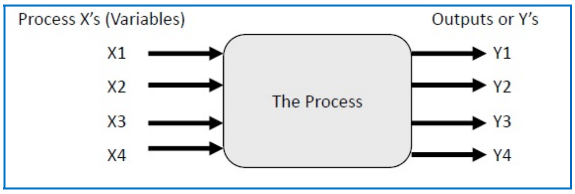

Fig. 1. *Model of design of experiments*

2. EXPERIMENTAL

Within the frames of this paper it was applied the six-sigma DMAIC methodology for improving the production process of composite pipes. The quality needs of the composite pipes were defined: resistance on high interior pressure and the important entries that influence on the improved solution. The proposed model for improving of the production process of composite pipes is presented in Fig. 2.

The composite pipes were produced based on epoxy resin as a matrix and glass fibers as reinforcement. The impregnation of the fibers and their winding was carried out on a laboratory filament winding machine MAW FB 6/1 manufactured from Mikrosam A.D. The basis of this process includes winding of resin impregnated fibers into a tool (mandrel) and hardening of the wound structure. Glass fibers pass through a resin bath and gets wet before winding operation. After the winding of the fibers the composite pipes were fully curing at temperature of 80ºC and 140ºC within 240 minutes on the both temperatures. After the curing operation, the removal of the mandrel from the specimens was performed. Glass/epoxy composite pipes were taken in this study because of the cost favorability compared to high performance fiber composite pipes.

During the impregnation of the fibers, several factors were observed (resin viscosity, speed of impregnation temperature, winding angle, fiber tension etc.) so that the required resin content in the composite pipes was attained (mass ratio fiber resin was 75:25 wt. %.).

There are lot of factors that influence the process, but there are only tree important that have a big influence on the output which we have used in the experimental design:

- the winding speed of the glass fibers (factor 1),
- fiber tension (factor 2),
- winding angle (factor 3).

Next step was determination of the factor levels as shown in the Table 1, namely for the first factor the low and high levels are set at 5, 25 m/min and 21 m/min, respectively, second factor – at 64N and 110N, respectively, and for the third factor – at 10º and 90º. Each factor has two factor levels, a low one and a high one. The low one has the value of (-1), the high one has a value of (+1). There are two factor levels with p = 2 and eight combinations (N= 8):

$$N = p^k = 2^3 = 8 \quad (1)$$

where: N = combinations; k = factors; p = factor levels.

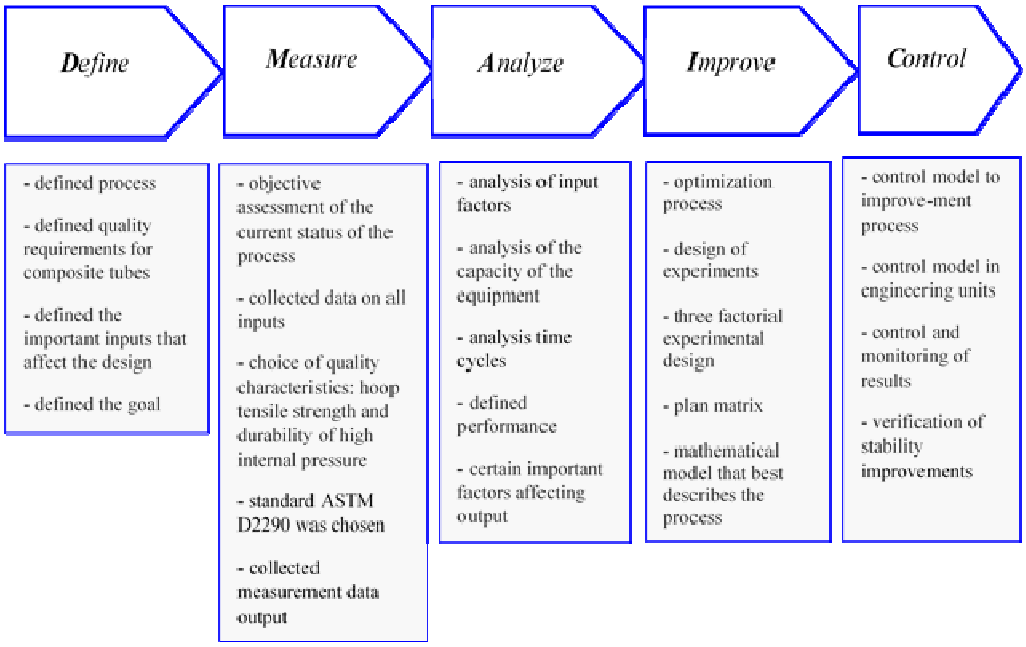

Fig. 2. *- Six sigma DMAIC proposed model for improving the production process of composite pipes*

For the statistical analysis two tests of each combination were realized so the number of replications is two. With that assumption, we took the first order linear model with interactions to predict the response function i.e. the hoop tensile strength of the composite pipes within the stated study domain (5,25– 21) m/min x (64 - 110)N x (10-90)º.

The full factorial experimental design allows making mathematical modeling of the investigated process in the vicinity of a chosen experimental point within the study domain [3,4]. To include the whole study domain we chose the central points of both ranges to be the experimental points. For the winding speed of the composites, we chose the experimental point to be 13,125 m/min, for the fiber tension – 87N and for the winding angle, the experimental point – 50º (which corresponds to previously defined levels).

All tests were conducted with a biaxial/combined loading of split-disk test specimens according to ASTM D2290 [2].

Table 1 *- Factor levels*

	p = 2	(-1)	(+1)
x_1	winding speed (m/min)	5,25	21
x_2	fiber tension (N)	64	110
x_3	winding angle (º)	10	90

3. RESULTS AND DISCUSSION

The test results with two replications of each combination together with the experimental matrix are presented in Table 2. The statistical parameters Y - the arithmetic mean of the results and s_i^2 - the variance of the results were calculated at first. By implementing the 2^3 factorial experimental design we found out that the response function in coded variables, *yk*, is:

$$y = 411.6599 + 25.2749x_1 + 2.9239x_2 + 391.274x_3 - 12.060x_1x_2 + 24.5001x_1x_3 - 0.4874x_{23} - 12.8089x_1x_2x_3 \quad (2)$$

In the experimental design the terms x_1x_2, x_1x_3, x_2x_3 and $x_1x_2x_3$ are the interaction between the factors which might also have the influence on the response, in our case hoop tensile strength (Y value). By analyzing the regression equation it should be noted that the main positive contribution to the Y is given by the winding angle i.e. hoop tensile strength is directly proportional to the winding angle of the fibers in the composite pipes. The influence of the winding angle of the fibers is ten orders of magnitude greater than the influence of the winding velocity but the influence of the fiber tension is the lowest. The interaction of the two factors, has a negligible effect on the hoop tensile strength which is smaller than the influence of the factors separately. The interaction of the three factors, with the coefficient of – 12. 8089 also has a negligible negative effect on the hoop tensile strength.

***Table 2** -Results of the experiments*

N	Experimental matrix							Results of experiments			
	x_1	x_2	x_3	$x_1 x_2$	$x_1 x_3$	$x_2 x_3$	$x_1 x_2 x_3$	y_1	y_2	Y	s_i^2
1	-1	-1	-1	+1	+1	+1	-1	895.36	765.19	830.28	8472.1
2	+1	-1	-1	-1	-1	+1	+1	827.70	733.23	780.47	4462.3
3	-1	+1	-1	-1	+1	-1	+1	898.36	851.92	875.14	1078.3
4	+1	+1	-1	+1	-1	-1	-1	699.90	751.79	725.85	1346.3
5	-1	-1	+1	+1	-1	-1	+1	24.80	25.84	25.32	0.5408
6	+1	-1	+1	-1	+1	-1	-1	22.03	22.52	22.58	0.1201
7	-1	+1	+1	-1	-1	+1	-1	16.55	17.45	17.00	0.4050
8	+1	+1	+1	+1	+1	+1	+1	16.83	17.07	16.95	0.0288
										Σ	15360.1
										Σ / 8	1920.0

From the regression equation it can be noted that only the winding angle as a process parameter x_3 influence significantly on hoop tensile strength. The influence of the other two factors: winding speed and tension of the fiber affect insignificantly on the tensile strength, and also there is no interaction between factors.So, they can be omitted in the regression equation:

$$y = 411.6599 + 391.274x_3 \quad (3)$$

The test which compares the formula and the results of the experiments were made by using the Fisher's criteria (Table 3). The values for Y_P are calculated by using formula 2. If the variability of the model is smaller than the experimental standard deviation, then the model can be accepted and further bused (Formulas 4 - 7).

$$Fp \le Ft\ (95\%) \tag{4}$$

$$F_p = \frac{S_{ad}^2}{S_i^2} \tag{5}$$

$$S_{ad}^2 = \frac{\sum_{j=1}^{N}(Y - Y_p)^2}{f} \tag{6}$$

$$f = N - (p+1) = 8 - (2+1) = 5 \tag{7}$$

Based on the calculation of the differences between calculated and experimental values it was found that Fp=1.308163. The tabular value for Fisher's criteria for 95%, f=5 and N=8 is 3.69 and that means that the model is adequate. Because of the fact that the variability of the model is smaller than the experimental standard deviation the model can be accepted and further be used.

Table 3 *- Calculation of the differences between calculated and experimental values*

N								**Results of calculated and experimental values**		
	x_1	x_2	x_3	$x_1\ x_2$	$x_1\ x_3$	$x_2\ x_3$	$x_1\ x_2\ x_3$	**Y**	Y_p	$(Y - Y_p)^2$
1	-1	-1	-1	+1	+1	+1	-1	830.28	765.19	499.299
2	+1	-1	-1	-1	-1	+1	+1	780.47	733.23	754.33
3	-1	+1	-1	-1	+1	-1	+1	875.14	851.92	4517.18
4	+1	+1	-1	+1	-1	-1	-1	725.85	751.79	6736.47
5	-1	-1	+1	+1	-1	-1	+1	25.32	25.84	24.3049
6	+1	-1	+1	-1	+1	-1	-1	22.58	22.52	3.553225
7	-1	+1	+1	-1	-1	+1	-1	17.00	17.45	11.4921
8	+1	+1	+1	+1	+1	+1	+1	16.95	17.07	11.8336
									Σ	12558.46
									Σ ÷ 5	2511,69

4. CONCLUSION

In the frame of this paper six sigma DMAIC methodology was applied to improve the industrial process - production of the composite pipe. Based on the six sigma proposed model, the design of the experiments i.e. three factorial experimental design was applied for improving of the process. The important entries that influence on the improved solution were defined.For the range of the winding speed, winding velocity and winding angle the experimental measurements of the tensile strength of composite pipes were carried out by implementing the 2^3 full factorial experimental design. A correlation equation was established for tensile strength as a function of the winding speed, winding velocity and winding angle of the fibers and of the interaction between them.

Namely, it was created the regression equitation which the best describes the process. From the regression equitation it was concluded that the winding angle, as a process parameter, has the greatest influence on the strength of the composite pipes. Therefore, the bigger angle leads to a greater hoop tensile strength of the composite pipes.

It was observed that if the study domain is precisely established (narrow enough), the factorial experimental design can be employed in order to give good approximation of the response. It was made verification of the model i.e. the adequacy of the regression equation and it was found that the model is adequate and can be accepted and further used.

The composite pipes are good replacement for the conventional metal pipes in terms of quality and price and they may be successfully applied in many industries for fluid transport, for reservoirs and cisterns for chemicals and fuel.

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SIX SIGMA I DIZAJN EXPERIMENTA U CILJU POBOLJŠANJA PROIZVODNJE KOMPOZITNIH CEVI

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REZIME

U radu je analizirana mogućnost unapređenja proizvodnje kompozitnih cevi primenom Six Sigma DMAIC metodologije. U prvom delu rada definisani su zahtevi kvaliteta takvih cevi, pre svega otpornost na visoki unutrašnji pritisak, kao i važnost ulaznih podataka koji utiču na krajnji rezultat. Dizajniranje je sprovedeno u cilju poboljšanja industrijskog procesa proizvodnje takvih cevi. Eksperiment je realizovan na bazi plan matrice pri čemu su izrađena 8 modela kompozitnih cevi. Tri glavna uticajna parametra su uzeta u obzir: brzina, napon u vlaknima i ugao pletenja (uvijanja). Korišćen je tro- faktorijalni metod planiranja eksperimenta sa dva nivoa varijacije 2^{3}.
U eksperimentalnom delu rada izrađeni su modeli cevi na bazi epoksilnih smola (matrica) i staklenih vlakana (ojačanje). Impregnacija sa vlaknima kao i njihovo uvijanje je sprovedeno u laboratorijskim uslovima na mašini MAW FB 6/1, proizvođača Mikrosam A.D.
Kod svih izrađenih cevi napon u zidu cevi je testiran u laboratorijskim uslovima. Na bazi tako dobijenih rezultata kreirana je regresiona jednačina koja na optimalni način opisuje proces. Regresiona jednačina upućuje na zaključak da ugao uvijanja vlakana ima najveći uticaj na jačinu kompozitnih cevi.
Ključne reči: *six sigma, dizajn eksperimenta, plan matrica, pletenje vlakana, kompozitni cevi, zatezna čvrstoća.*