TECHNICAL TRANSACTIONS 12/2018
MECHANICS
DOI: 10.4467/2353737XCT.18.191.9679
SUBMISSION OF THE FINAL VERSION: 13/11/2018

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Using the Taguchi method to optimize controlled variables in the experiment to produce a Ti coating by cold spraying

Optymalizacja zmiennych kontrolowanych w wytwarzeniu powłoki Ti metoda zimnego natrysku

Abstract
The article presents a method for optimizing technological parameters utilizing the G. Taguchi procedure. Optimization algorithm of controlled variables was presented in order to obtain the greatest value of nanohardness, microhardness and elastic modulus.

Keywords: optimization, orthogonal array, nanohardness, microhardness, elastic modulus.

Streszczenie
W artykule przedstawiono metodę optymalizacji parametrów technologicznych wykorzystującą procedurę G. Taguchi. Zaprezentowano algorytm optymalizacji zmiennych kontrolowanych, tak by uzyskać jak największą wartości nanotwardości, modułu elastyczności i mikrotwardości.

Słowa kluczowe: optymalizacja, tablice ortogonalne, nanotwardość, mikrotwardość, moduł elastyczności.

1. Introduction

Production of coatings with required properties is the major research challenge. In the manufacturing process it is necessary to indicate controllable parameters and properties expected from the resulting coating. A multitude of controlled parameters and their values make a large number of combinations effects high costs. It is necessary to minimize the number of test experiments. The objective is to select the best combination of control parameters so that the product is most robust. Statistical methods allow for minimizing the number of experiments [1]. One such method is the method of G. Taguchi, which was used in this study. The purpose of the research was to determine the value of technological parameters (controlled variables): the hardness H, the elastic modulus E and the microhardness $HV_{0.3}$ assume the highest value. The Cold Spray technique was used to produce a Ti coating. The G. Taguchi method with P4, L3 orthogonal table for optimization was used.

2. Experimental

The quality of the experiment requires specifying necessary steps to ensure proper quality of work, They include a determination of input parameters, the range of values of controlled variables, the range of permissible changes in the parameter value and the establishment of a research plan – experimental planning. The next step is to conduct an experiment. This is a very time consuming and laborious stage. The results obtained should be analyzed statistically. This is the most important stage in terms of interpretation of results and elimination of possible errors. Determining controlled parameters has the greatest impact on the outcome of the process. The final stage is to identify the variables controlled to ensure realization of this objective. Orthogonal arrays are not unique to Taguchi. They were discovered earlier. However, Taguchi has simplified their use by providing tabulated sets of standard orthogonal arrays and corresponding linear graphs to fit specific projects [2]. A typical tabulation is present in Table 1 (P = 4, L = 3).

Table 1. Orthogonal array P = 4, L = 3

Taguchi, P = 4, L = 3				
Run	**P1**	**P2**	**P3**	**P4**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

In this array, the columns are mutually orthogonal. That is, for any pair of columns, all combinations of factor levels occur; and they occur an equal number of times. Here there are four parameters P1-P4, each at three levels L. This is called an "L 9" design, with 9 indicating the nine rows. Specific test characteristic for each experimental evaluation are identified in the associated row of the table (Run). Thus, L 9 means that nine experiments are to be carried out to study four variables at three levels. That is that design reduces 81 (3^4) configurations to 9 experimental evaluations.

Ti powder was used to coat the coatings. The establishment of well-defined technological parameters is the major aspect of quality control. Hardness (H), elastic modulus (E), HV were taken into account. The present objective of experiments focuses on the selection of control parameters to obtain the highest H, E, HV. The G. Taguchi method contains system design, parameter design, and tolerance design procedures to achieve a robust process and result for the best product quality [3, 4]. The base of Taguchi's techniques is the use of parameter design which is an engineering method for product design that focuses on determining parameter settings producing the best levels of quality characteristic with minimum variation. G. Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally over a variety of conditions [3, 4]. The concept of loss function, quality of the signal to noise ratio (S/N) and orthogonal tables [5, 6] is essential in the Taguchi method..

In the experiment, the larger the better method was used: (nanohardness, elastic modulus, HV)

$$Tta = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \qquad (1)$$

where:

n – number of measurements,

y – analyzed feature.

In this experiment, 4 controlled factors (T, p, d, V) can take 3 values as indicated in Table 2. The number of experiments is equal to the number of combinations L^P.

Orthogonal tables of parameters P = 4 and number of levels L = 3 were prepared for the experiments. The best suitable orthogonal array is L_9 [4, 5, 7]. The use of 9 experiments have allowed for effective optimization by the G. Taguchi method. The following table shows the values of the controlled variables.

Table 2. The values of the controlled factors used in the preparation of a coating on the substrate of Ti Al 7075

T (°C)	p (bar)	d (mm)	V (mm/s)
700	30	30	300
750	37	40	400
800	45	50	500

After the experiment, the distribution of the results obtained was checked by applying a normal curve to the diagram. Before optimization, basic ANOVA was carried out.

3. Results and discussion

As mentioned above, the control parameters were, among others, hardness H and modulus of elasticity E obtained for the load of 20 mN and loading rate of 80 mN/min. For each of the 9 configurations, 49 measurements were made to form a 180 × 180 μm map containing measurement points every 30 μm (Fig. 1).

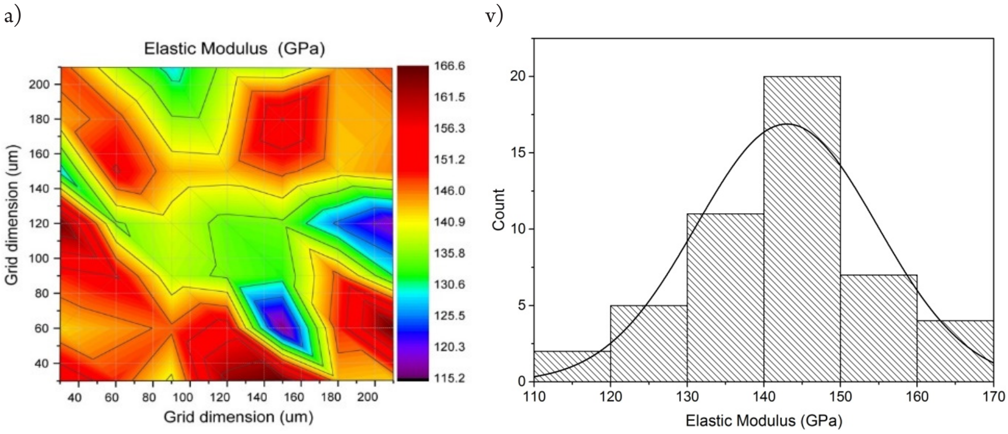

Fig. 1. Map of 49 measurement points obtained for load 20 mN and loading rate 80 mN/min: a) map of elastic modulus, b) distributions ot the elestic modulus and normal curve

A normal distribution occurs for most of the values. Deviation of the curve is resulted by the heterogeneity of the coating structure Fig. 1b). Before Taguchi optimization, the normal distribution of the tested values was checked. After performing all 9 experiments, optimal parameters were determined using the method indicated by G. Taguchi [7]. The following tables show the basic statistical parameters characterizing the results.

Table 3. Average value of Eta and expected S/N ratio under optimum conditions T = 800°C, p = 45 bar, coatings distance d = 50 mm, V = 500 mm/s

Effect	Average Eta by Factor Levels (Ti na Al) Mean = 12.8679 Sigma = 1.02618 Level	Means	Paramet. Estimate	St.Dev.	St.Error
TEM	T-70C	12.43975	-0.428146	1.708753	0.573454
	T-75C	12.75096	-0.116940	0.520015	0.316349
	T-80C	13.41298	0.545085	0.529871	0.319333
PRESS	p-30	12.56622	-0.301677	1.816080	0.591189
	p-37	12.87566	0.007760	0.224669	0.207937
	p-45	13.16182	0.293917	0.772893	0.385673
DYST	dyst-30	11.87318	-0.994719	1.225356	0.485613
	dyst-40	13.30697	0.439070	0.192684	0.192567
	dyst-50	13.42355	0.555649	0.661100	0.356692
V	V-300	12.22128	-0.646615	1.550298	0.546219
	V-400	13.09531	0.227407	0.808561	0.394471
	V-500	13.28711	0.419209	0.432011	0.288341

Factor	Expected S/N Ratio under Optimum Conditions (Ti na Al) Mean = 12.8679 Sigma = 1.02618 * - effect excluded from model Level	Effect Size	Standard Error
{1}TEM	T-80C	0.54509	0.297873
*PRESS	p-45	0.29392	
{3}DYST	dyst-50	0.55565	0.297873
{4}V	V-500	0.41921	0.297873
Expected S/N		14.38784	

Table 3 shows the best configuration of control parameters, while the following Figure 2 presents the influence of control factors on Eta-value. The pressure has a smaller influence on

Eta, and coating distance has a bigger one. The average Eta for this group of parameter is 12.87. The graphical presentation of control factors indicates their individual impact on Eta (Fig. 2).

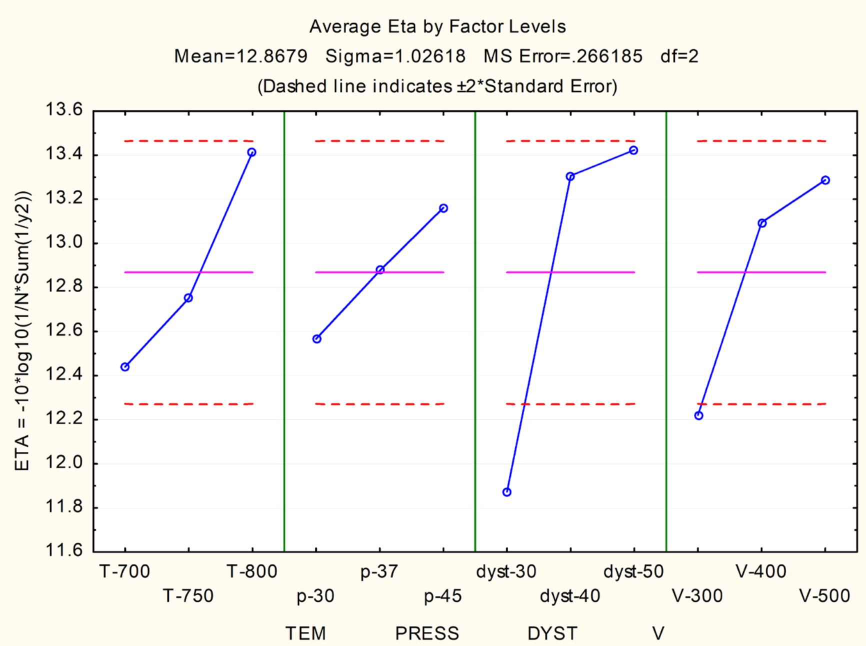

Fig. 2. The influence of individual control factors on the Eta value calculated as the bigger the better

Table 4 shows the values of the control parameters under which H, E and HV take the highest values.

Table 4. Indication of control parameters in S/N group the larger the better

sample	parameters	*T* (°C)	*p* (bar)	Coating distance (mm)	*V* (mm/s)	S/N
Ti 7075	HV, H, E,	800	45	50	500	14.38

From the group of 9 experiments, one was selected using the Taguchi method.

4. Conclusion

An overview of the Taguchi method has been presented and the steps involved in the method were briefly described. Overall, the Taguchi method is a powerful tool which can offer simultaneous improvements in quality and cost. Furthermore, the method can aid integrating costs and engineering functions through the concurrent engineering approach required to evaluate cost over the experimental design. The article presents the Taguchi method applied for the process of optimization and its application in the area of surface engineering. An example is presented of the method application for the optimization of the parameters value of technological parameters necessary to obtain the required coating of Ti. Application of Taguchi method for scatter value optimization enables one to decrease the number of needed experiments even if there is a deviation from the normal distribution. The optimization process succeeded. The Ti coatings significantly improved their properties as expected.

The Taguchi method emphasizes pushing quality back to the design stage, seeking to design a product which is insensitive or robust to causes of quality problems. It is a systematic and efficient approach to determining the optimum experimental configuration of design parameters for performance, quality, and cost. Principal benefits include considerable time and resource savings; determination of important factors affecting operation, performance and cost; and quantitative recommendations for design parameters which achieve the lowest cost, high quality solutions.

The work reported herein has been undertaken as part of the Additive Manufacturing Processes and Hybrid Operations Research for Innovative Aircraft Technology Development. Project founded by the National Center for Research and Development under the INNOLOT Programme.

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If you want to quote this article, its proper bibliographic entry is as follow: Makrenek M., Żórawski W., Góral A., *Using the taguchi method to optimize controlled variables in the experiment to produce a ti coating by cold spraying*, Technical Transactions, Vol. 12/2018, pp. 179–184.