ANALELE UNIVERSITĂȚII
"EFTIMIE MURGU" REȘIȚA
ANUL XV, NR. 1, 2008, ISSN 1453 - 7397

Cosmin Laurenţiu Ionescu, Ioan Nicoară, Corina Gruescu

The Integration of Classic and Taguchi Experimental Design into the Projection and Optimization of the Process Parameters in the Controlled Laser Processing of Polycarbonate Cogwheels

By using classic and Taguchi experimental design one can optimize the laser processing of plastic cogwheels, the experiments presented here exploring the correlation between the laser parameters and their optimal nominal values, so that the shape, dimensions and state indices of the cogwheels surface can be controlled and the economic efficiency of the process can be maximal. The method using Taguchi experimental design can be regarded as a particular application of classic experimental design. Taguchi experimental design treats in a unitary way the average and variability of the measured characteristics (the dispersion). Plastic cogwheels obtained using nonconventional technologies (CO2 laser processing) are used in particular for prototypes because of their high productivity and low costs as compared to those obtained using conventional technologies.

Keywords: *laser, Taguchi, cogwheels, surface quality*

1. Introduction

Generally, when a dispersion or an instability of the production characterisitcs of a product are detected, one identifies and reduces or eliminates the causes that produced them. Taguchi system works totally different. Instead of trying to eliminate these parasite factors (called noise factors), it tries to minimize their impact.

The implementation of robust Taguchi engineering keeps to Deming's principle PDCA (**P**lan - **D**o - **C**heck - **A**ct) which comprises the following steps:

1. defining the project aim
2. defining the system limits

3. defining the M entry signal, the y exit signal and the ideal function
4. developing signal and noise strategies
5. defining the controlled factors and their levels
6. formulating the experiment and preparing for it
7. doing the experiment, collecting data
8. analyzing data
9. doing a confirmation experiment
10. documentation and implementation of the results
11. planning the next steps.

The factors referring to the product or its fabrication process (laser cutting of cogwheels) that we can easily control are called *controlled factors*.

In the laser cutting process these parameters are as follows:

A – speed
B – power
C –time of impulse
D – pause time
E – defocusing
F – gas flow

Looking for good values for the controlled factors is done experimentally, in order to optimize the product or the process so that they may:

- observe the wished functional performance, in this case, the processed surface quality: $R_a \approx 0{,}8\ \mu m$
- be robust, that is insensitive to noise factors

This paper will analyze the case of the six factors mentioned above, each with two levels and one interaction. To optimize the factors in order to obtain the wished roughness for cogwheels processed surface I used both the classic and Taguchi experimental design.

The two levels I chose to analyze for each factor were selected in accordance with an interval of variation and a centre of the experiment.

In Table 1 there are presented the two levels of the six controlled factors.

Table 1

	Factors	Level 1	Level 2
A	speed	3000 mm/min	4500 mm/min
B	power	170 W	180 W
C	time of impulse	5 ms	3 ms
D	pause time	3 ms	5 ms
E	Defocusing	d 4 mm/5 mm	d 4 mm/2,5 mm
F	Gas flow	20 l/min	10 l/min

Using the above mentioned data five cogwheels were processed for each different combination of factors according to the configuration of the experiment plans and roughness was measured for each sample.

The real state of the samples surface was considered a target criterion considering the fact that this represents a factor of direct influence on the constructive elements behavior in all situations. Although difficult to evaluate through explicate analytic relations, the influence of the surface state is manifest on a group of parameters: the portant capacity, the friction coefficient, the resistance to wearing through, adhesion or corrosion, the fiability of the superficially deposed layers, namely aspect

Irrespective of the material used or the processing technology, mechanical items are affected by errors in shape and roughness. The discrete character of the material used and the imperfections generated by any technological process in real conditions lead to the impossibility of obtaining ideal, perfectly plane cylindrical, spherical surfaces.

2. Classic experimental designs

The practical procedure of doing an experimental design comprises the following stages:

a. A quality criterion to optimize is considered (the quality of the processed surface – roughness) of the type (R_a = 0,8). Six factors at two levels are considered necessary A (speed), B (power), C (time of impulse), D (pause time), E (defocusing), F (gas flow) and an interaction between A and B.
b. The smallest matrix compatible with the experiment aims is looked for. An L8 matrix is chosen in which column 3 was reserved for the study of A and B interaction.

Table 2

No. trials	Controlled factors						
	A	**B**	**Int. AB**	**C**	**D**	**E**	**F**
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

c. five cogwheels for each combination of factors are made

d. for each trial an average of the five measurements is calculated and a general T average is established for all answers.
A table with the results of the trials is drawn. (table 3).

Table 3

No. trials.	Controlled factors							Measurements values					
	A	B	AB Int.	C	D	E	F	no.1	no.2	no.3	no.4	no.5	Average
1	1	1	1	1	1	1	1	1,027	0,895	0,977	0,944	0,867	**0,942**
2	1	1	1	2	2	2	2	1,498	1,32	1,242	1,52	1,591	**1,434**
3	1	2	2	1	1	2	2	0,496	0,712	0,525	0,725	0,714	**0,634**
4	1	2	2	2	2	1	1	1,415	1,189	1,145	1,337	1,379	**1,293**
5	2	1	2	1	2	1	2	1,275	1,282	1,354	1,175	1,305	**1,278**
6	2	1	2	2	1	2	1	1,092	0,982	0,969	1,092	0,928	**1,013**
7	2	2	1	1	2	2	1	1,104	0,987	0,978	1,054	1,058	**1,036**
8	2	2	1	2	1	1	2	1,175	1,179	1,165	1,164	1,151	**1,167**

e. the average answer for each level of each factor is calculated, corresponding to the average of all trials results in which the respective factor is at that level. For example:

$$\overline{A}_1 = \frac{\overline{x}_1 + \overline{x}_2 + \overline{x}_3 + \overline{x}_4}{4}, \quad (1)$$

$$\overline{A}_2 = \frac{\overline{x}_5 + \overline{x}_6 + \overline{x}_7 + \overline{x}_8}{4} \quad (2)$$

The T general average corresponds to the central value of the average answers for the levels of each factor:

$$\frac{\overline{A}_1 + \overline{A}_2}{2} = \overline{T} \quad (3)$$

f. the average effect of each level of the factors is calculated
g. similarly, the average answer of AB interaction is established and a table with the answers is drawn (table 4).

$$E_{A1} = \overline{A}_1 - \overline{T}\,;\; E_{A2} = \overline{A}_2 - \overline{T}\,;\; E_{A1} = -E_{A2} \quad (4)$$

Table 4

No. factor	Effect on measured value			
	level 1		level 2	
A	E_{A1}	-0,024	E_{A2}	0,024
B	E_{B1}	0,067	E_{B2}	-0,067
AB	$E_{(AB)1}$	0,045	$E_{(AB)2}$	-0,045
C	E_{C1}	-0,127	E_{C2}	0,127
D	E_{D1}	-0,161	E_{D2}	0,161
E	E_{E1}	0,070	E_{E2}	-0,070
F	E_{F1}	-0,029	E_{F2}	0,029

h. the values in the table with answers are graphically drawn

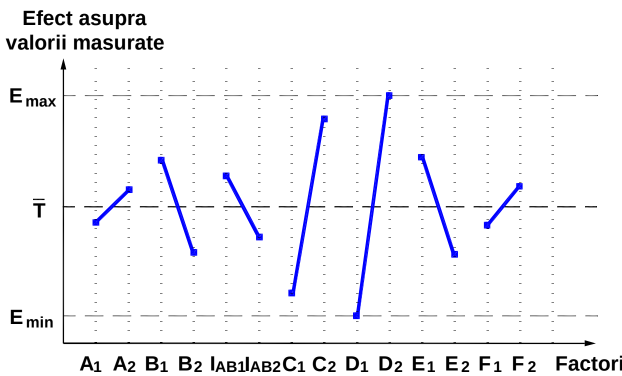

Figure 1. Graphic with answers

To present into more detail the effect of the AB interaction on the measured value, the relative values of the different possible combinations A_1B_1, A_1B_2, A_2B_1, A_2B_2 are analyzed.

- the average answer for each possible combination is calculated:

$$\overline{A}_1\overline{B}_1 = \frac{\overline{x}_1 + \overline{x}_2}{2};\ \overline{A}_1\overline{B}_2 = \frac{\overline{x}_3 + \overline{x}_4}{2};\ \overline{A}_2\overline{B}_1 = \frac{\overline{x}_5 + \overline{x}_6}{2};\ \overline{A}_2\overline{B}_2 = \frac{\overline{x}_7 + \overline{x}_8}{2} \tag{4}$$
$$\overline{A}_1\overline{B}_1 = 1{,}188;\ \overline{A}_1\overline{B}_2 = 0{,}964;\ \overline{A}_2\overline{B}_1 = 1{,}145;\ \overline{A}_2\overline{B}_2 = 1{,}102$$

- the average effect of E_{A1B1} interaction comprises the effects of the levels A_1 and B_1 as well as the value of I_{A1B1} interaction, if it exists:

$$E_{A1B1} = E_{A1} + E_{B1} + I_{A1B1} \tag{5}$$

but it results that:

$$E_{A1B1} = \overline{A}_1\overline{B}_1 - \overline{T} = (\overline{A}_1 - \overline{T}) + (\overline{B}_1 - \overline{T}) + I_{A1B1} \tag{6}$$

whence the value of I_{A1B1} interaction

$$I_{A1B1} = \overline{A}_1\overline{B}_1 - \overline{T} - (E_{A1} + E_{B1}) \tag{7}$$
$$I_{A1B1} = 0{,}045;\ I_{A1B2} = -\ 0{,}045;\ I_{A2B1} = -\ 0.045;\ I_{A2B2} = 0{,}45$$

i. the experiment matrix modifies to calculate directly the four possible values of AB interaction by replacing the figures in column 3, telling the interaction, with the values in 1, 2, 3, 4 corresponding to the four possible combinations mentioned before. The L8 matrix with the explanation of the AB interaction is presented in table 5.

Table 5

No. trials	Controlled factors						
	A	B	AB	C	D	E	F
1	1	1	A_1B_1	1	1	1	1
2	1	1	A_1B_1	2	2	2	2
3	1	2	A_1B_2	1	2	2	1
4	1	2	A_1B_2	2	1	1	2
5	2	1	A_2B_1	1	1	2	2
6	2	1	A_2B_1	2	2	1	1
7	2	2	A_2B_2	1	2	1	2
8	2	2	A_2B_2	2	1	2	1

j. the levels of the factors are identified so that they optimize the taget criterion according to the following aspects:
- the factors that most influence the target criterion (R_a) are identified and their optimal levels are chosen.
- the non-influential factors are chosen by economic criteria
- supposing all factors are at their optimal levels their individual averages are added
- the value $R_{a\ theoretical}$ is estimated using only the major effects of the factors and their interactions (this is done so because with the experiment error divided within each calculated average there is the possibility of an overestimation)

$$R_{a\ teoretic} = \overline{T} + \sum(E) + \sum(I)$$

$$\begin{aligned} R_{a\ teoretic} &= \overline{T} + E_{A1} + E_{B2} + E_{C1} + E_{D2} + E_{E2} + E_{F1} + E_{IAB2} = \\ &= 1{,}1 + (-0{,}024) + (-0{,}067) + (-0{,}127) + (0{,}161) + \\ &+ (-0{,}070) + (-0{,}029) + (-0{,}045) = 0{,}899 \end{aligned} \quad (8)$$

To calculate the resulting theoretical value of the cogwheel surface roughness, when all the factors are at their optimal levels, their effects are added.

The optimal levels of the processing parameters resulting after the optimization with classic experimental design to reach the target value of roughness are:

$$\mathbf{A_1\ B_2\ C_1\ D_2\ E_2\ F_1}$$

k. an attempted validation through the physical checking of the hypothesis of additivity of the effects of all factors and interactions is made.

3. Taguchi experimental designs

The practical procedure of realizing a Taguchi experimental design comprises the following steps:

a. an R_a target quality criterion to optimize is established and the stages of classic analysis are applied

b. the standard deviation $s_1, s_2,...,s_8$ of each series of measurements is eatblished

$$s = \sqrt{\frac{\sum (y_i - \overline{y})^2}{n-1}} \tag{9}$$

c. the ratio S/N for each series of measurements is calculated and the average $\overline{T}_{S/N}$ for the S/N answers is calculated.

d. a table is drawn with the answers and parameters calculated before. The results of the trials, averages, standard deviations, S/N ratios, Table 6

Table 6

No trials	Controlled factors							Measured values							
	A	B	AB	C	D	E	F	nr.1	nr.2	nr.3	nr.4	nr.5	Average	Standard deviation	S/N [dB]
1	1	1	1	1	1	1	1	1,027	0,895	0,977	0,944	0,867	0,942	0,064	23,353
2	1	1	1	2	2	2	2	1,498	1,32	1,242	1,52	1,591	1,434	0,147	19,775
3	1	2	2	1	1	2	2	0,496	0,712	0,525	0,725	0,714	0,634	0,114	14,876
4	1	2	2	2	2	1	1	1,415	1,189	1,145	1,337	1,379	1,293	0,119	20,714
5	2	1	2	1	2	1	2	1,275	1,282	1,354	1,175	1,305	1,278	0,065	25,870
6	2	1	2	2	1	2	1	1,092	0,982	0,969	1,092	0,928	1,013	0,075	22,606
7	2	2	1	1	2	2	1	1,104	0,987	0,978	1,054	1,058	1,036	0,053	25,819
8	2	2	1	2	1	1	2	1,175	1,179	1,165	1,164	1,151	1,167	0,011	40,513

e. the average S/N answer for each factor level is calculated corresponding to the average of S/N ratios of all trials in which the factor is at that level. Similarly, the average S/N answer relating to the interactions is calculated, e.g.

$$\overline{A}_{1,S/N} = \frac{(S/N)_1 + (S/N)_2 + (S/N)_3 + (S/N)_4}{4}, \tag{10}$$

$$\overline{A}_{1,S/N}\overline{B}_{1,S/N} = \frac{(S/N)_1 + (S/N)_2}{2}. \tag{11}$$

f. the average S/N effect of each factor level is calculated as compared to the average S/N answers the value of interactions is calculated. For example:

$$E_{A1,S/N} = \overline{A}_{1,S/N} - \overline{T}_{S/N}, \tag{12}$$

$$I_{A1B1,S/N} = \overline{A}_{1,S/N}\overline{B}_{1,S/N} - \overline{T}_{S/N} - \left(E_{A1,S/N} + E_{B1,S/N}\right). \tag{13}$$

g. tables are drawn with answers to factors and interactions (tables 7 and 8)

Table 7

No. factor	Effect on S/N ratio			
	Level 1		Level 2	
A	$E_{A1,S/N}$	-4,504	$E_{A2,S/N}$	4,504
B	$E_{B1,S/N}$	-1,305	$E_{B2,S/N}$	1,305
C	$E_{C1,S/N}$	-1,715	$E_{C2,S/N}$	1,715
D	$E_{D1,S/N}$	1,164	$E_{D2,S/N}$	-1,164
E	$E_{E1,S/N}$	3,417	$E_{E2,S/N}$	-3,417
F	$E_{F1,S/N}$	-1,075	$E_{F2,S/N}$	1,075

Table 8

Interaction	A_1B_1	A_1B_2	A_2B_1	A_2B_2
Effect on S/N ratio	$I_{A1B1,S/N}$	$I_{A1B2,S/N}$	$I_{A2B1,S/N}$	$I_{A2B2,S/N}$
Measured Value	3,200	-3,200	-3,200	3,200

h. the values in the S/N answers table are drawn graphically (fig. 2)

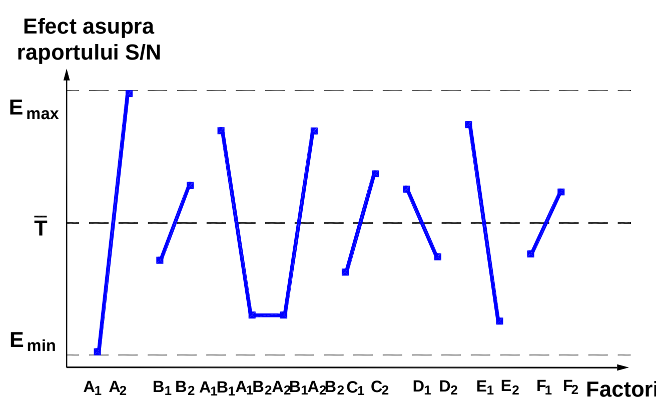

Figure 2 Graphic with S/N answer values

i. the factors levels are established taking into account the following:
- the factors with the greatest influence on the S/N ratio are identified and the proper levels are chosen so that the algebric value of the S/N ratio may be as high as possible.
- the non influential factors are chosen by economic criteria
- supposing all factors are at their optimal levels their individual S/N effects averages are added
- the value û of the S/N ration is estimated using only the major effects of the factors and interactions (this is done so because with the experiment

error divided within each calculated average there is the possibility of an overestimation):

$$\hat{\mu} = \bar{T}_{S/N} + \sum(E_{S/N}) + \sum(I_{S/N}) = 34,991 \text{ db} \quad (14)$$

- the value of R_a target criterion is estimated:

$$\begin{aligned} R_{a\ teoretic} &= \bar{T} + \sum(E) + \sum(I) = \\ &= \bar{T} + E_{A2} + E_{B2} + E_{C1} + E_{D1} + E_{E1} + E_{F1} + E_{IA1B1} = \\ &= 1,1 + (0,024) + (-0,067) + (-0,127) + (-0,161) + \\ &\quad + (0,07) + (-0,029) + (0,045) = 0,855 \end{aligned} \quad (15)$$

The levels of the processing parameters resulting after the optimization with Taguchi experimental design to reach the target value of roughness are:

A_2 B_2 C_1 D_1 E_1 F_1

4. Conclusions:

- The technology of processing mechanical items by using controlled laser cutting depends on a number of factors whose influence and interdependence cannot be quantified and classified intuitively
- To find an optimal combination of the influence factors with direct consequences on the statistic parameters of the items quality is to use some mathematical methods, among which the robust Taguchi project is a real success.
- Practically the optimization of the process allows that by using a certain equipment some high quality items may be produced, efficiently and accurately, which could very hardly be produced if random combinations of the processing factors were used
- A rise in quality represents a significant improvement of the quality statistic parameters (a decrease and symmetry in dispersion, an average close to the nominal value), with the direct consequence being that of the rise in the conformity degree of the items in a certain lot.

References

[1] Alexis, J. (1999):*Metoda Taguchi în practica industriala*, Editura Tehnica, Bucuresti

[2] Bounds, M., ş.a. (1994): *Beyond Total Quality Management Toward the Emerging Paradigm* – McGraw-Hill International Editions, NY, USA

[3] Broh, R.A. (1982): *Managing Quality for Higher Profits* – McGraw-Hill, NY, USA

[4] Clausing, D. (1998): *Product Development, Robust Design and Education* – 4th Annual Total Product Development Symposium, ASI, 1998.

[5] Cross, N., Clausing, D. (1994): *Total Quality Development* – MIT Press, Cambridge, MA, USA
[6] Cross, N., ş.a. (1994): *Engineering Design Methods* – John Wiley & Sons, Chicester
[7] Chang, R.Y. (1995):Continuous process improvement –Kogan Press, London
[8] Diamond, W.J. (1981): *Practical Experiment Designs* – Lifetime Learning Publications, Belmont, CA, USA
[9] Ealey, L.A. (1990): *Les méthodes Taguchi dans l'industrie occidentale* – Les Editions D'Organisation, Paris
[10] Fowlkers, W.Y., Creveling, C.M. (1997): *Engineering Methods for Robust Production Design Using Taguchi Methods în Technology and Product* – Addison-Wesley
[11] Pugna, A., Grozescu, I., Ştefănescu, W., Proştean, G. (2006): *Optimizing the hydrothermal growth process parameters of the α-quartz monocrystals using Taguchi's Robust Design* –, Virtual Design and Automation - New Trends in Collaborative Design, Poznan, Poland, Publishing House of Poznan University of Technology, pg. 327-336.
[12] Taguchi, G. (1986): *Introduction to quality engineering. Designing quality into products and process*, Asian Productivity Organization
[13] Taguchi, G., ş.a. (2000): *Robust Engineering* –McGraw-Hill, New York
[14] Taguchi, G. (1987): *System of Experimental Design* – Vol I & II, Unipub/Kraus International Publications, White Plains, NY, USA
[15] Taguchi, G. (1986): *Introduction to Quality Engineering* – Unipub/Kraus International Publications, White Plains, NY, USA
[16] Taguchi, G., Wu, Y. (1980): *Introduction to off-line quality control* – Central Japan Quality Association, Nagoya, Japan
[17] Taguchi, G., ş.a. (1989): *Quality Engineering in Production Systems* – McGraw-Hill, NY, USA

Addresses:

- Dr. Eng. Cosmin Laurenţiu, University "POLITEHNICA" of Timişoara, ionescucosminlaurentiu@gmail.com
- Prof. Dr. Eng. Ioan Nicoară, University "POLITEHNICA" of Timişoara, inicoara@mec.upt.ro
- Conf. Dr. Eng. Corina Gruescu, University "POLITEHNICA" of Timişoara, corina_gruescu@yahoo.com