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Experimental optimization of process parameters in laser cutting of polycarbonate gears

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1. Introduction

Polycarbonate is widely used due to its mechanical, optical, thermal and chemical properties. Tensile strength (55 - 75 MPa), Young's modulus (2 - 2.4 GPa) and hardness (~70HRC) recommend the material also for manufacturing of gears, which work with low power or special conditions transmissions. Moulding and extrusion, commonly used to machine polycarbonate pieces, are not appropriate to obtain complex shape and preciseness as gears require. Also, the usual cutting technology of gears is long-lasting and inefficient if some faster machining process can be found. Generally speaking, specially designed technologies must be designed and implemented for machining particular materials or parts [1 - 2]. In the present case a nonconventional technology, for instance laser cutting suites much better.

Still, laser cutting is not very simple to apply. Targets regarding piece's characteristics (precision in shape and dimension, roughness, thermal side-effects etc.), time of machining and energetic supply needed, are hard to attain without a process optimization. The large number of parameters involved, exclude the choice by random of their values. There are optical, electrical and mechanical factors, which influence the laser cutting process. Different combinations of their possible values might satisfy requirements to attain different target criteria (diverse in nature and value). From optical standpoint, laser cutting is a nonimaging application. The quality of the optical system included in the structure of a laser cutting machine, influences directly the general traits of the process. Flexibility and preciseness are required in order to ensure easy transforming of radiant beam's properties (spot size, defocus facilities, and variable energetic density).

Control of electrical parameters, such as power supply, ensures appropriate energetic properties of the cutting beam (for pulse lasers, also pulse duration and pause duration are very important).

Mechanical design of the nozzle, precision and speed of cutting head's displacement are involved in accuracy and efficiency of machining. Establishing the most suited combination of values for all these parameters needs a mathematical approach. There are several optimization process methods, among which, the Taguchi method proved to be one of the best.

The subject of machining is a set of four gears making part of a two – step transmission. Geometrical complexity, precision of tooth pitch, roughness of flanks, variety of modulus and number of teeth recommend a flexible technology such as laser cutting.

2. Experimental equipment

Effective machining of sample pieces was achieved using an existing laser cutting machine, whose optical system was improved [3 - 6]. The computer aided equipment uses a CO_2 pulse laser source, 2 kW power. The machine belongs to C.A.L.F.A. laboratories at I.U.T. Bethune, Universite d'Artois, France. A general image and the scheme of the machine are presented in Fig. 1.

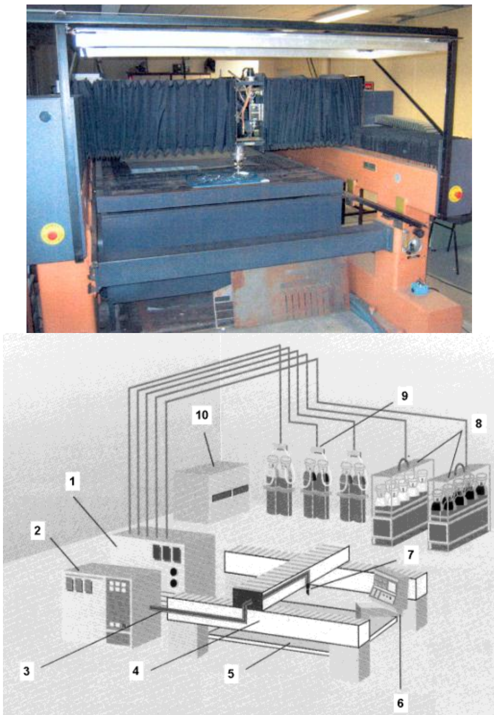


Fig. 1 Image and scheme of the laser cutting machine: *1* - power supply block, *2* - CO_2 laser source, *3* - optical beam path, *4* - mechanical structure, *5* - material to machine, *6* - numerical command block, *7* - cutting head, *8* - assemblies to provide and control auxiliary gas (He, Ar, N_2, O_2), *9* - assembly for CO_2 supply, *10* - cooling block

The general features of the laser cutting machine are wavelength, μm; beam divergence, deg; emitted power, W; cutting speed, mm/s; vertical position of the spot, duration of pulse and pause, ms; chemical nature, pressure and flow of the gas, distance between nozzle and piece, mm; nozzle's internal geometry and exit diameter. Some of these parameters are fixed so their values can not be changed. Others are variable within certain ranges and can be used to optimize the machining process.

3. General design of the experimental optimization program

The plan on which the optimization program developed is briefly presented in Fig. 2.

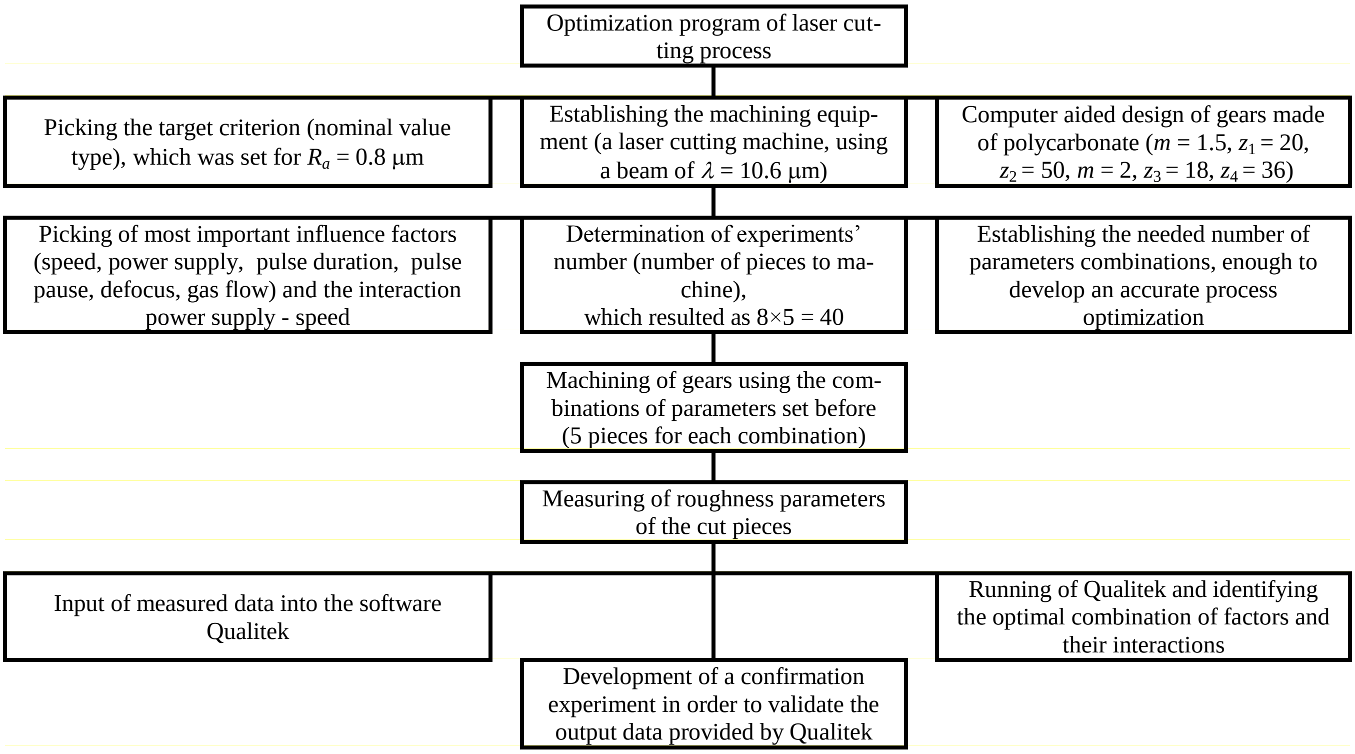


Fig. 2 Logical and chronological scheme for the experimental program development

4. Choice of influence parameters and working combinations in order to apply Taguchi method in process optimization

Traditional quality optimization methods search for dispersion or unsteadiness of a product's feature and aim to reduce or eliminate causes. Taguchi strategy introduces the concept of noise for the sources which spoil quality and states that minimization of noise – factors' impact brings in better efficiency in processes optimization [7 - 9].

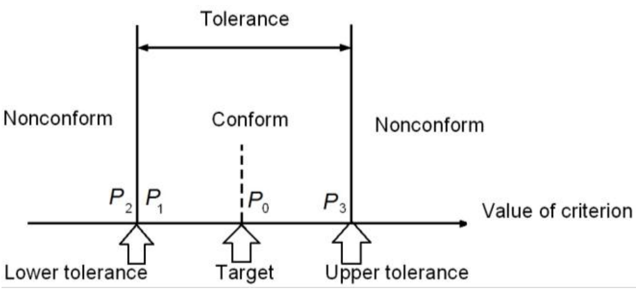


Fig. 3 Taguchi concept base. Difference of quality between product P_1 (still good) and P_2 (unacceptable) is very small. Difference between P_1 and P_3 (still good) is very large. The best product is P_0 (value of criterion equal to the target)

Accordingly to Genichi Taguchi's concept (Fig. 3), loss of quality occurs not only if the product is outside the tolerance limits, but even if it is inside these limits. The quadric function of quality loss, defined by Taguchi for target criteria is mathematically expressed as:

$$L(y) = k(y - y_N)^2 \tag{1}$$

where: $L(y)$ is the value of loss expressed in currency/product; y is the value of the quality feature involved; y_N is the nominal value (target); k is a constant to quantify global financial loss.

For a sample containing n pieces, measuring allows computation of mean value $\bar{y}$ and standard deviation s. The function of quality loss becomes

$$L(y) = ks'^2 = k\left[s\left(\frac{y_N}{\bar{y}}\right)\right]^2 = k{y_N}^2\frac{s^2}{\bar{y}^2} \tag{2}$$

In relation (2) k and y_N are constant, so that loss minimization requires maximization of the ratio $\bar{y}^2/s^2$, which mathematically corresponds to tendency $n \to \infty$. The expression of the signal/noise ratio for target criteria is given in relationship (3)

$$\frac{S}{N} = 10log\left[\frac{\bar{y}^2}{s^2} - \frac{1}{n}\right] \quad [dB] \tag{3}$$

The complete factorial experiments plan studies all possible combinations of selected factors' levels. Theoretically, they are complete. However, the time needed for experiments is very long and costs are very high (for instance, an experiment involving 15 factors at 2 levels requires 2^{15}=32768 pieces).

The fractional factorial experiments plan is based on the idea that certain possible combinations of factors provide enough efficient information, so that the number of effective experiments may be considerably reduced. Table 1 presents a complete factorial experiment in a classic version for 3 factors at 2 levels. Table 2 shows a complete factorial Taguchi plan.

Tables 3 and 4 illustrate two alternatives of fractional factorial Taguchi plan. In order to compute the effects of an independent factor, the experimental plan must be orthogonal.

Table 1

Complete classic experimental plan

		C1	C2
A1	B1	R1	R2
	B2	R3	R4
B1	B1	R5	R6
	B2	R7	R8

Table 2

Complete Taguchi experimental plan

Nr. exp.	Factors under study A B C			Result of experiment
1	1	1	1	R1
2	1	1	2	R2
3	1	2	1	R3
4	1	2	2	R4
5	2	1	1	R5
6	2	1	2	R6
7	2	2	1	R7
8	2	2	2	R8

Table 3

Fractional experimental Taguchi plan (alternative I)

Nr. exp.	Factors under study A B C			Result of experiment
1	1	1	1	R1
4	1	2	2	R4
6	2	1	2	R6
7	2	2	1	R7

Table 4

Fractional experimental Taguchi plan (alternative II)

Nr. exp.	Factors under study A B C			Result of experiment
2	1	1	2	R2
3	1	2	1	R3
5	2	1	1	R5
8	2	2	2	R8

Triangle shaped tables and linear graphs are associated to the most of standard Taguchi matrices and are used to define columns which study interactions. Taguchi method, generally, uses a standard *L*8 matrix (Table 5).

Practical procedure to fulfil a Taguchi experimental plan assumes the creation of a table, containing influence parameters, measured values and responses (Table 6).

It is necessary to compute the mean effect *S/N* of each level's factor and the value of interactions related to the mean value of response *S/N*. Responses related to factors and interactions are written in matrices.

Table 5

Standard L8 matrix

Nr. exp.	Factors under study							Result of experiment
	A	B	C	D	E	F	G	
1	1	1	1	1	1	1	1	R1
2	1	1	1	2	2	2	2	R2
3	1	2	2	1	1	2	2	R3
4	1	2	2	2	2	1	1	R4
5	2	1	2	1	2	1	2	R5
6	2	1	2	2	1	2	1	R6
7	2	2	1	1	2	2	1	R7
8	2	2	1	2	1	1	2	R8

Table 6

Complete table of parameters, measured values and responses

Nr. exp.	Factors under study						Int	Measured values							
	A	B	C	D	E	F	AD	nr.1	nr.2	nr.3	nr.4	nr.5	mean	s	S/N[dB]
1	1	1	1	1	1	1	1	x11	x12	x13	x14	x15	$\bar{x}_1$	s1	(S/N)1
2	1	1	1	2	2	2	2	x21	x22	x23	x24	x25	$\bar{x}_2$	s2	(S/N)2
3	1	2	2	1	2	2	1	x31	x32	x33	x34	x35	$\bar{x}_3$	s3	(S/N)3
4	1	2	2	2	1	1	2	x41	x42	x43	x44	x45	$\bar{x}_4$	s4	(S/N)4
5	2	1	2	1	1	2	3	x51	x52	x53	x54	x55	$\bar{x}_5$	s5	(S/N)5
6	2	1	2	2	2	1	4	x61	x62	x63	x64	x65	$\bar{x}_6$	s6	(S/N)6
7	2	2	1	1	2	1	3	x71	x72	x73	x74	x75	$\bar{x}_7$	s7	(S/N)7
8	2	2	1	2	1	2	4	x81	x82	x83	x84	x85	$\bar{x}_8$	s8	(S/N)8

For the given application, a set of parameters, considered to be the most influent on the process of machining, were selected. They are speed, power supply, duration of pulse, duration of pause, defocus and gas flow.

For each of the six parameters above, two levels and one interaction was set. That means 2^7 experiments are needed. The optimization criterion was established to be the value of flank roughness parameter R_a. The target is "nominal value" type (R_a = 0.8 μm). Further mathematical approach is based on fractional factorial experiments plans provided by Taguchi method. These plans considerably reduce the number of required experiments (to only 8). Table 7 indicates the values of the process factors for 8 combinations (*A*…*H*).

Table 7

Values of factors considered for combinations *A*…*H*

Combination	Speed, mm/min	Power, kW	Interaction level	Duration of pulse, ms	Duration of pause, ms	Nozzle distance, mm	Gas flow, l/min
A	3000	170	1	5	3	4/5	20
B	3000	170	1	3	5	4/2.5	10
C	3000	180	2	5	3	4/2.5	10
D	3000	180	2	3	5	4/5	20
E	4500	170	1	5	3	4/5	10
F	4500	170	1	3	5	4/2.5	20
G	4500	180	2	5	3	4/2.5	20
H	4500	180	2	3	5	5	10

5. CAD of gears and generation of NC code

The laser cutting equipment used to machine the gear samples is supplied together with the software Laser *DX*3, which is an extension of AutoCAD so it is able to import to *.dxf files. Dimensioning and geometrical calculus of the transmission with total transmission ratio i = 4 was accomplished and for each type of gear an AutoCAD drawing was saved in *.dxf format. Flank shape is normal convolute. First step of the transmission needed a modulus $m_{1,2}$ = 1.5. The second one was dimensioned at $m_{3,4}$ = 2. The four types of gears machined for the experiment are shown in Fig. 4.

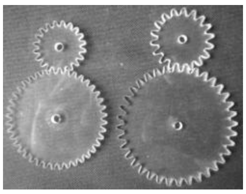


Fig. 4 Four types of gears machined for the experiment with the laser cutting machine: $m_{1,2}$ = 1.5, z_1 = 20, z_2 = 40, $m_{3,4}$ = 2, z_3 = 18, z_4 = 36

The numerical command file, adapted to the management file format, specific to the machine's software allows the transfer of the numerical code from Laser *DX*3 to equipment's computer. The numerical code translates the drawing of the piece into complete commands regarding entrance and exit points of the nozzle, displacement of the cutting head along a path, which reproduces the contour of the piece, displacement segments without cutting and so on.

6. Experimental results

Five gears were machined for each of parameters combinations (*A*…*H*). Each gear sample was measured with a Mahr electronic measuring device. Table 8 presents the results of measurement. Odd columns of the table indicate the combination (*A*….*H*) and denote the sample (*A*1…*A*5….*H*1…*H*5). Even columns contain the measured values of R_a. The last line indicates the mean value of the parameter R_a, for a given combination.

Table 8

Parameter R_a - Combinations *A*…*H*

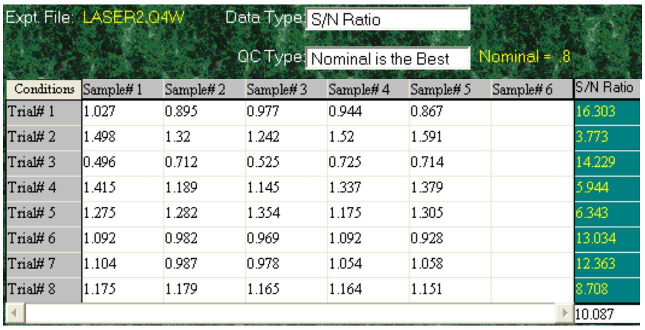
A	R_a	*B*	R_a	*C*	R_a	*D*	R_a	*E*	R_a	*F*	R_a	*G*	R_a	*H*	R_a
1	1.02	1	1.49	1	0.49	1	1.41	1	1.27	1	1.09	1	1.10	1	1.17
2	0.89	2	1.32	2	0.7	2	1.18	2	1.28	2	0.98	2	0.98	2	1.17
3	0.97	3	1.24	3	0.52	3	1.14	3	1.35	3	0.96	3	0.97	3	1.16
4	0.94	4	1.52	4	0.72	4	1.33	4	1.17	4	1.09	4	1.05	4	1.16
5	0.86	5	1.59	5	0.71	5	1.37	5	1.30	5	0.92	5	1.05	5	1.15
	0.94		1.43		0.63		1.29		1.27		1.01		1.03		1.16

7. Optimization of process parameters by means of Taguchi method

The complex array statistical calculus required by Taguchi method implementation needs automated computation. The appropriate software Qualitek was run in order to process the numerical data.

The program builds the inner array accordingly to fractional factorial experiments plan and uses for the terms in array the measured values of roughness (R_a parameter) from Table 8.

The window in Fig. 5 displays data type, which is "signal/noise ratio", optimization criterion type, which is "nominal is the best". Nearby the criterion type is written the target value of the criterion, R_a = 0.8 μm.



Expt. File: LASER2.Q4W Data Type: S/N Ratio
QC Type: Nominal is the Best Nominal = .8

Conditions	Sample# 1	Sample# 2	Sample# 3	Sample# 4	Sample# 5	Sample# 6	S/N Ratio
Trial# 1	1.027	0.895	0.977	0.944	0.867		16.303
Trial# 2	1.498	1.32	1.242	1.52	1.591		3.773
Trial# 3	0.496	0.712	0.525	0.725	0.714		14.229
Trial# 4	1.415	1.189	1.145	1.337	1.379		5.944
Trial# 5	1.275	1.282	1.354	1.175	1.305		6.343
Trial# 6	1.092	0.982	0.969	1.092	0.928		13.034
Trial# 7	1.104	0.987	0.978	1.054	1.058		12.363
Trial# 8	1.175	1.179	1.165	1.164	1.151		8.708
							10.087

Fig. 5 *S/N* ratio, mean values, optimization criterion and target value

Bellow these settings, all 40 values are put into a matrix, where each line corresponds to a certain combination of parameters. The last column shows the *S/N* ratio of each line.

Finally, an optimal combination of factors resulted. It is presented in Fig. 6.

The program predicts an *S/N* ratio of ~18 (initially it was ~10), which means that using the optimum parameters the roughness of pieces will get values much more gathered around the target. Next window summarizes the current status and expected status properties of the process (Fig. 7).

Column # / Factor	Level Description	Level	Contribution
1 viteza	4500 mm/min	2	.024
2 puterea	180 W	2	.223
3 INTER COLS 1 x 2	*INTER*	1	.199
4 timpul de impuls	5 ms	1	2.222
5 timpul de repaus	3 ms	1	2.981
6 duza / distanta d	d4mm / 2.5 mm	2	.762
7 debitul de gaz	20 l/min	1	1.823

Fig. 6 Optimal combination of factors and interaction levels and expected value of *S/N* ratio

Fig. 8 shows graphically the scattering of results corresponding to current state and predicted one. One can notice that for the current state the distribution curve is displaced with respect to the target. In optimal conditions, the dispersion is much less than ±3σ (limited by vertical lines). The frequency curve presents a peak ~2.5 higher and a narrow aperture centred about the target vertical line.

In order to validate the theoretical optimization, a confirmation experiment was achieved. A set of five sam-

Fig. 7 Current status and expected status properties of the process

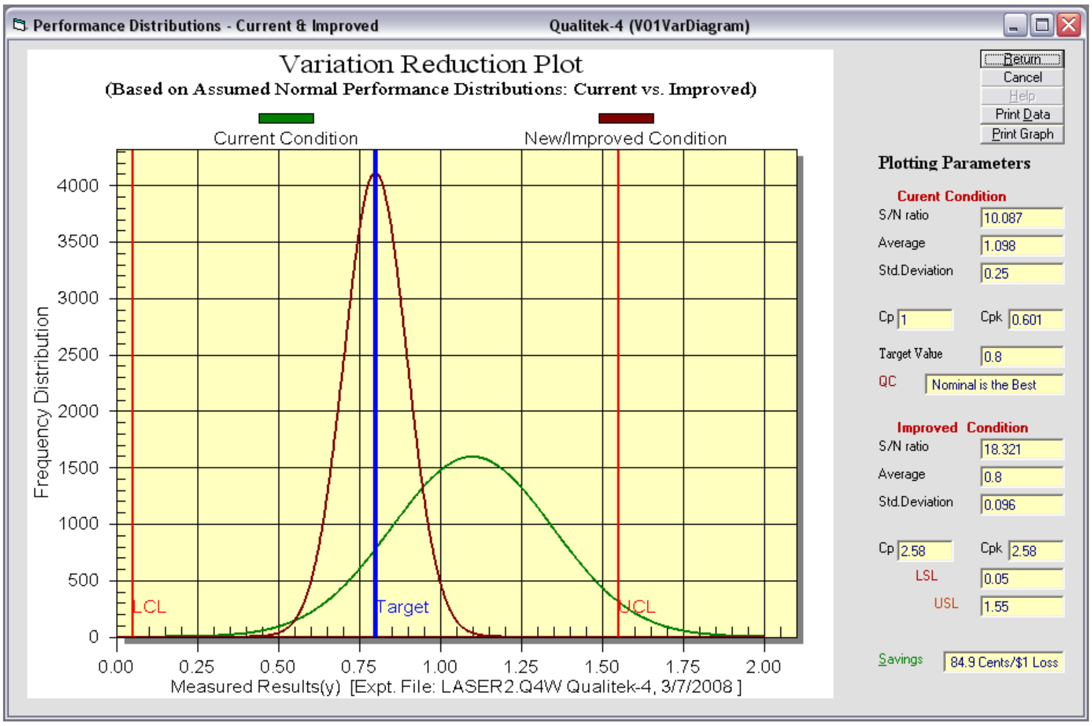


Fig. 8 Graph of reduced variation for optimal factors compared to initial ones (under the hypothesis of normal distribution)

ple gears were machined using the optimal combination of factors indicated by Qualitek (Fig. 6). The pieces were measured and the results are presented in Table 9.

Table 9

Roughness parameters (confirmation experiment)

Sample	1	2	3	4	5	Mean R_a
R_a	0.80	0.78	0.83	0.89	0.71	0.806

Table 10

Comparative data regarding initial, predicted and practically achieved conditions

Feature	Initial conditions	Estimated conditions	Validation experiment
S/N ratio	10.087	18.321	24.459
Mean value	1.098	0.800	0.805
Standard deviation	0.250	0.096	0.047

The analysis of data got with the confirmation experiment indicates a better value of *S/N* ratio (24.459) than the predicted one (18.321).

Quality statistical data of the pieces machined at experimentally chosen parameters improved substantially after optimal values were used in a confirmation experiment (Table 10).

8. Conclusions

Fractional factorial experiments plans stated by Taguchi method and a specialized software – Qualitek – proved to be quick, economic (only 40 samples needed effective machining for optimizing six parameters in two levels and one interaction organized in 8 combinations) and very efficient. For the pieces machined in optimal conditions S/N ratio is even better than the predicted one. The mean value is very close to the nominal target, which significantly improves the quality of the lot of pieces. The machining becomes very precise, considering the optimization criterion. As well, the process itself becomes desirable instead of traditional technology. Auxiliary devices such as moulds were totally eliminated and the machining duration decreased considerably (3 - 4 minutes/piece in function of number of teeth).

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EKSPERIMENTINIS POLIKARBONATINIŲ KRUMPLIARAČIŲ LAZERINIO PJOVIMO PROCESO PARAMETRŲ OPTIMIZAVIMAS

R e z i u m ė

Polikarbonatinės detalės dažniausiai yra liejamos arba štampuojamos. Detalių matmenų ir formos tikslumui padidinti reikalingos naujos technologijos, iš kurių priimtiniausias yra lazerinis pjovimas. Detalių kokybė (matmenų ir formų tikslumas, šiurkštumas, šalutiniai šiluminiai efektai), proceso energijos sąnaudos ir efektyvumas gali būti optimizuojami tik matematiniais metodais.

Straipsnyje pristatomas Taguchi metodo pritaikymas polikarbonatinių krumpliaračių lazeriniam pjovimui projektuoti. Mažiausiam bandinių skaičiui nustatyti septynių kintamųjų procese taikomas dalinio faktorialo eksperimentų planavimo metodas. Tikslo kriterijus yra krumplių šonų šiurkštumas, o panaudoto optimizacijos kriterijaus tipas – „nominalus yra geriausias“. Efektyvaus bandomų krumpliaračių apdirbimo ir jų šiurkštumo parametro Ra_{DIN} matavimo duomenys yra panaudoti programoje Qualitek. Ši programa nustato optimalius įtakos veiksnių dydžius ir prognozuoja signalo ir paklaidų laipsnį bei statistinius detalių apdirbimo, naudojant optimizacijos rezultatus parametrus. Labai gera detalių kokybė ir didelis proceso efektyvumas yra patvirtinti eksperimentais.

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EXPERIMENTAL OPTIMIZATION OF PROCESS PARAMETERS IN LASER CUTTING OF POLYCARBONATE GEARS

S u m m a r y

Polycarbonate pieces are usually moulded or extruded. Accurate dimensions and shape of complex pieces need new technologies, among which laser cutting is preferred. Quality of pieces (dimensional and shape precision, roughness, thermal side – effects), power supply and efficiency of the process can be optimized only through mathematical approach.

The paper presents an application of Taguchi method in designing the laser cutting of polycarbonate made gears. Fractional factorial experiments plans are used to establish the minimum number of experiments needed for a seven – variable process. The target criterion is the roughness of gears' flank and the chosen optimization criterion type is "nominal is the best". Effective machining of sample gears and measurement of their roughness parameter R_{aDIN} provided data, which was introduced into the program Qualitek. The software displayed optimal values of the influence factors and predicted signal/noise ratio and statistical quality parameters of the pieces machined using the results of optimization.

Very good quality of pieces and high efficiency of process resulted throughout a confirmation experiment.

Keywords: laser cutting, polycarbonate gears.

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