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QUALITY CONTROL AND OPTIMIZATION OF A LASER CUTTING SYSTEM FOR CUTTING 10MM MILD STEEL USING DOE SOFTWARE

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Abstract: Quality is a major attribute seriously considered in industry. Consumers, producers, support personnel focus on it from different perspectives. Conformance quality considered by the producers needs to meet the specification quality of a product/service and also the degree that it is reliable, maintainable or sustainable. The study below aims to help increase the quality level by proposing an optimization of a Laser Cutting System for 10mm Mild Steel used in automobile industry. Experimental results made on 32 rectangular samples (1250x2500x10mm) will show how the laser cutting parameters influence the surface roughness and hence the surface quality of the work pieces (mild steel S355JR). The laser parameters (input) were: feed rate (*v*), gas pressure (*p*), power (P), frequency (f) and efficiency, while the response was the roughness (R_z), [2]. Design of experiment (DOE) software based on the design of a 2^5 factorial experiment was used to optimize the cutting process by minimizing the R_z value and maximizing the feed rate. The settings for the input parameters were chosen based on the pre-experimental tests. Using ANOVA analysis on the roughness model obtained, the authors were able to find the influence of each parameter and concordance of the model, as well as to get a more reliable model by taking in consideration the parameters' inter-influence, [2]. The reliability of the mathematical model obtained is also confirmed by the ANOVA analysis, indicating a good significance of the factors at a degree of reliability P=95%. From the performed analysis it was concluded that for any output value (R_z) we can obtain the proper combination of laser machine parameters using this model thus having eventually a positive financial effect on the production costs, [1].
Key words: design of experiments, laser cutting, experimental model, mild steel, roughness.

1. INTRODUCTION

This study implies executing the following steps: pre-optimization, experimental setup, data acquisition, data analysis, result interpretation, optimization and conclusions.

The laser system used for experimental tests is Mazak Super Turbo-X 48 Mk2 1800W (figure 1).

Fig. 1. Machine tool

32 rectangular samples of a mild Steel (S355JR), with the chemical composition given in Table 1 (given by the European standard EN 10025-2:2004 for hot-rolled structural steel. Part 2 - Technical delivery conditions for non-alloy structural steels), were cut at the following dimensions: 1250x2500mm and 10mm thickness.

Table 1. Chemical composition of S355JR mild Steel

C max [%]	**Mn max [%]**	**Si max [%]**	**P max [%]**
0.24	1.6	0.55	0.04
S max [%]	**N max [%]**	**Cu max [%]**	**CEV max [%]**
0.04	0.012	0.55	0.45

The main process parameters that can be modified are: feed rate (*v*), gas pressure (*p*), power (P), frequency (f) and efficiency. The range of cutting conditions were extended over the limits recommended by the laser system producer to fully observe the material behavior and it was used to determine the influence of the cutting parameters on the surface roughness (R_z quantified by the largest difference from peak-to-valley in μm), [3].

Measurements were performed using the roughness measuring equipment Mitutoyo SV-C 600 and analysed by Surfpak-SV 1.500 software (figure 2).

Fig. 2. Roughness measuring equipment

The design of experiments (DOE) software, used for the analysis steps, provides an extensive set of tools that helps to design experiments that are effective for studying the factors that may affect a product or process and analyze the results of such experiments. To sum up the main useful applications we can name the ability to identify the significant factors that affect a product or process and to evaluate ways to improve and optimize the design, [1].

Using DOE we will find a model based on the influence of the laser parameters to the output parameter (roughness R_z).

2. EXPERIMENTAL CONDITIONS

The experimental plan was pre-optimized using Design Expert software. Combinations of the cutting parameters performed by DOE software and roughness measurements are given in Table 2.

Before getting any information about the influence of the process parameters on the output studied (R_z), we need a complex mathematical relationship that shows the R_z variation. Every output value will be the average of the five passes of pick-up.

Table 2. Experimental plan

Std	Run	Factor 1 A: power [W]	Factor 2 B: frequency	Factor 3 C: efficiency [%]	Factor 4 D: feed rate [mm/min]	Factor 5 E: gas pressure [bar]	Response 1 Rz [µm]
28	1	1800	500	90	1350	1.2	25.851
23	2	1700	1000	100	1150	1.2	32.815
22	3	1800	500	100	1150	1.2	37.536
8	4	1800	1000	100	1150	0.6	26.010
15	5	1700	1000	100	1350	0.6	21.097
17	6	1700	500	90	1150	1.2	38.828
29	7	1700	500	100	1350	1.2	32.953
6	8	1800	500	100	1150	0.6	24.759
4	9	1800	1000	90	1150	0.6	24.822
26	10	1800	1000	90	1350	1.2	32.547
31	11	1700	1000	100	1350	1.2	26.443
14	12	1800	500	100	1350	0.6	20.901
27	13	1700	1000	90	1350	1.2	22.122
24	14	1800	1000	100	1150	1.2	31.662
25	15	1700	500	90	1350	1.2	19.590
11	16	1700	1000	90	1350	0.6	19.119
21	17	1700	500	100	1150	1.2	32.169
13	18	1700	500	100	1350	0.6	18.306
30	19	1800	500	100	1350	1.2	26.964
32	20	1800	1000	100	1350	1.2	23.081
12	21	1800	1000	90	1350	0.6	16.548
3	22	1700	1000	90	1150	0.6	25.383
19	23	1700	1000	90	1150	1.2	32.629
9	24	1700	500	90	1350	0.6	17.917
16	25	1800	1000	100	1350	0.6	21.153
2	26	1800	500	90	1150	0.6	19.385
1	27	1700	500	90	1150	0.6	22.661
10	28	1800	500	90	1350	0.6	18.296
20	29	1800	1000	90	1150	1.2	39.919
5	30	1700	500	100	1150	0.6	26.163
18	31	1800	500	90	1150	1.2	32.147
7	32	1700	1000	100	1150	0.6	22.069

The relevant results on the influence of two or more factors on the output variable, including their interaction (comparing the different sub-samples of data), is possible by defining a model for factorial experiments. The number of input parameters considered in the experiment (5 parameters in our case) will determine what type of experimental plan DOE will perform (2^5 level factorial design), figure 3.

2.1. Analysis and discussion of results

Design of experiments (DOE) techniques facilitates the identification of significant factors that may affect a product or process and it also optimizes designs. Moreover, DOE software provides the recommended analysis treatment for interval and proper censored data which is a real tool for reliability-related analyses, [1].

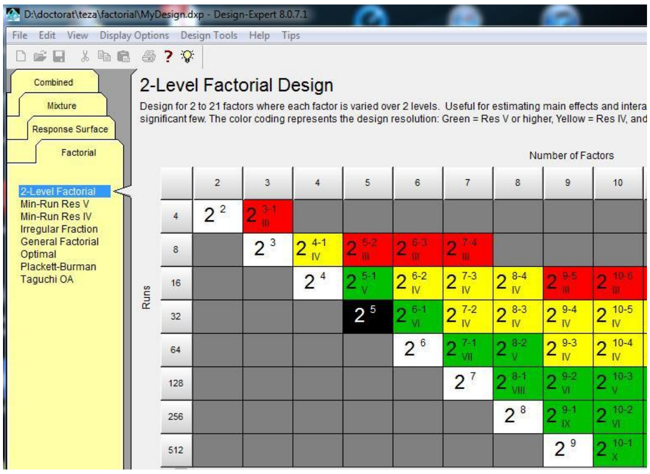

Fig. 3. 2^5- level factorial design

The Factorial model used is able to lead to a relevant model and ANOVA analysis for response surfaces reveals which of cutting parameters were relevant for the roughness change. The evaluation of the surface roughness was made by measuring the roughness value (R_z), with levels ranging from 16.548µm to 38.828µm.

To analyze the response, a Natural Log was chosen for a better output (figure 4).

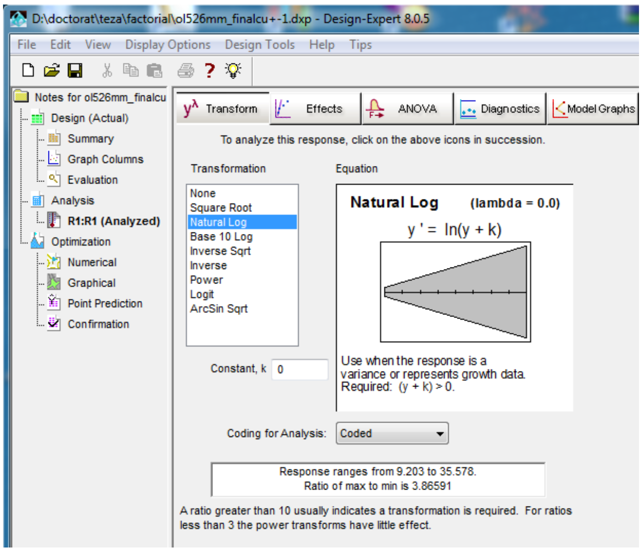

Fig. 4. Model analysis

Data analysis was conducted for a confidence interval α = 0.05%.

The value F = 17.41 for the model implies that the model is significant. Also the value of p<α (p= 0.0001; α = 0.05%) confirms that the model is significant and that there is just 0.01% chance that this model may be affected by noise.

The obtained results (p<α; p =0.0001; α = 0.05%). showed that the feed rate (*v)* and gas pressure (*p*) have a significant influence in obtaining the optimal surface roughness, as the table 3 presents.

Table 3. ANOVA analysis results

Response Rz						
ANOVA for selected factorial model						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F	
Model	1060.591017	6	1060.59102	17.4067186	<0.0001	significant
B-frequency	0.279939031	1	0.27993903	0.02756663	0.8695	
C-efficiency	8.320140281	1	8.32014028	0.81931492	0.3740	
D-feed rate	351.5822738	1	351.582274	34.6216039	<0.0001	significant
E-pressure	636.0585278	1	636.058528	62.6350305	<0.0001	significant
BC	35.77522578	1	35.7752258	3.5229185	0.0722	
DE	28.57491003	1	28.57491	2.81387684	0.1059	
Residual	253.8747175	25	10.1549967			
Cor total	1314.465934	31				

The estimated values of the coefficients, showed in table 4, which will build the equation model that will describe the relationship between input and output parameters.

Based on the output data introduced, the software recommended a polynomial regression which generated the following equation:

$$Ln(Rz) = +26.00 + 0{,}094 * freq + 0{,}51 * eff - 3.31 * feedrate + 4.46 * gaspress - \\ - 1.06 * freq * eff - 0.94 * feedrate * gaspress \quad (1)$$

Table 4. Estimated values of the coefficients

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High
Intercept	25.99515625	1	0.5633325	24.83495099	27.15536151
B-frequency	0.09353125	1	0.5633325	-1.06667401	1.25373651
C-efficiency	0.50990625	1	0.5633325	-0.65029901	1.67011151
D-feed rate	-3.31465625	1	0.5633325	-4.47486151	-2.15445099
E-pressure	4.45834375	1	0.5633325	3.29813849	5.61854901
BC	-1.05734375	1	0.5633325	-2.21754901	0.10286151
DE	-0.94496875	1	0.5633325	-2.10517401	0.21523651

The data correspond to a reliability of P=95%, (α= 5%) so the focus and interaction feed rate with gas pressure are significant model terms. Moreover the value of the Fisher test also proved that the model is significant.

The influence of the feed rate (*v*), and gas pressure (*p*) that are the most significant factors in this sequence are presented in figure 5.

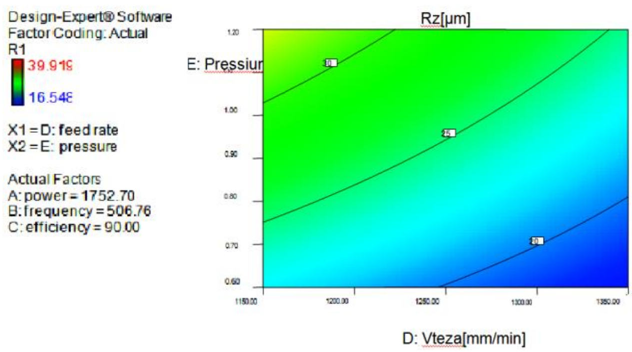

Fig. 5. The influence of the main factors

Figure 6 shows the 3D Surface plot of feed rate - gas pressure interaction.

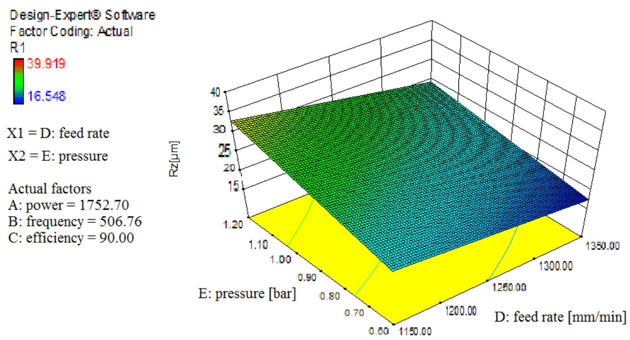

Fig. 6. The influence of the main factors

The figures 5 and 6 show that the roughness has a lower value at a high feed rate and low gas pressure.

The next step was the optimization of factors for a minimum roughness. Also we choose a maximum feed rate and a minimum gas pressure for a better profitability (figure 7 and table 5).

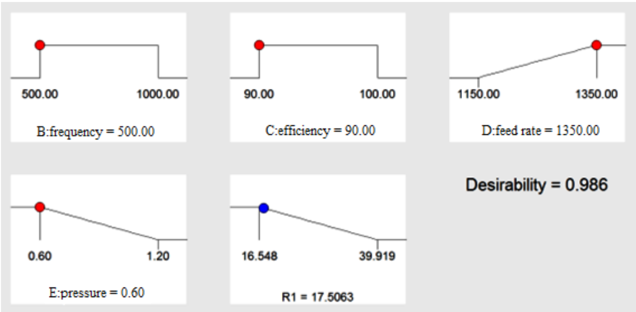

Fig. 7. Numerical optimization

Table 5. Constraints and limits

Constraints			
Name	**Objective**	**Lower limit**	**Upper limit**
B: frequency	is in range	500	1000
C: efficency	is in range	90	100
D: feed rate	maximize	1150	1350
E: gas pressure	minimize	0.6	1.2
R1	minimize	16.548	39.919

The program has calculated the optimal combination for input parameters for which you get the desired output (R_z). The result is shown in table 6.

Table 6. Desirability summary

Power [W]	Freq. [Hz]	Effic [%]	Feed rate [mm/ min]	Press [bar]	Rz [µm]	Desirability [0-1]
1800	500	90	1350	0.60	17.5	0.986

The next two figures (figure 8 and 9) represent the optimization result. That means we'll get a better desirability for the model at minimum gas pressure and maximum feed rate.

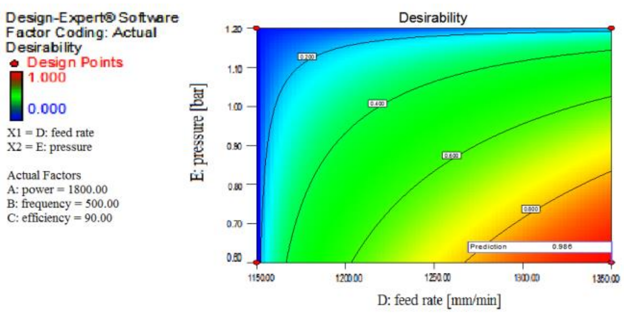

Fig. 8. Contour plot of Desirability

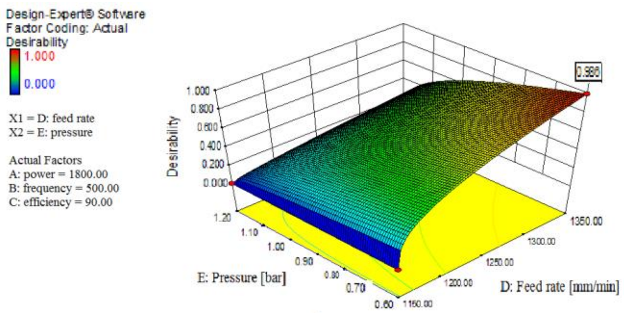

Fig. 9. 3D Surface plot of Desirability

Figure 10 presents the graphical optimization of the design for the interaction of gas pressure with the feed rate. Having a gas pressure of 0.6 bar and a feed rate of 2300 mm/min there is a predicted roughness of 14.6 µm.

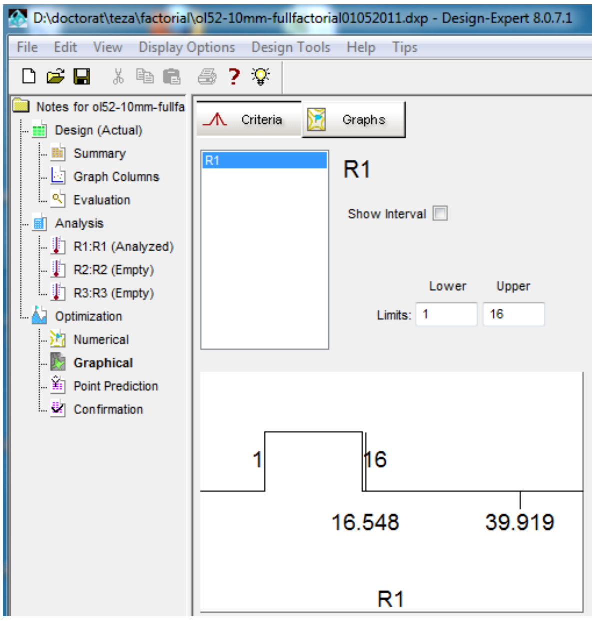

Fig. 10. Criteria limits

According to the standard (EN ISO 9013:2002) the roughness R_z is calculated according to the formulas:

- for the first quality class: R_z = 10 (0.6 x a:mm)µm;
- for the second quality class: R_z=40 (0.8 x a:mm)µm,

where a is the width of the cut.

Therefore, in order for the product to be located in the first class of quality, the maximum roughness should be R_z = 10 + 0.6 x 10 = 16µm and for it to be in quality class 2, maximum roughness should be R_z = 40 + 0.8 x 10 = 48µm.

The figure 11 shows that we can predict an optimal value for R_z=17.5 µm for a combination of input parameters P=1800 W, Frequency=500 Hz Efficiency=90%, Feed rate=1350 mm/min and Pressure=0.6 bar.

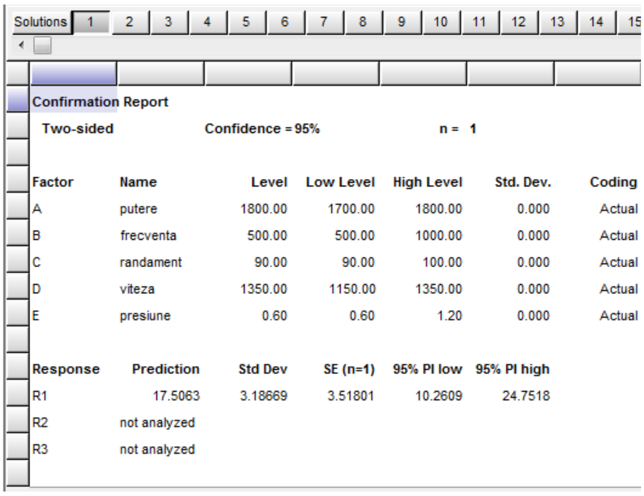

Fig. 11. Point prediction

3. CONCLUSION

This experimental study has shown the surface roughness improvement with respect to the influence of the cutting parameters. The cutting process was performed by the variation of feed rate (*v)*, gas pressure (*p*), power (P), frequency (f) and efficiency. The Design Expert software was used in pre-optimization, to improve the optimum/minimum number of samples that are required to be machined for extracting the correct and complete data.

The ANOVA analysis also indicates that the frequency does not have a significant contribution to the surface roughness variation. The experiment led to a significant mathematical model, also confirmed by the ANOVA analysis that indicated a good significance of the factors at a degree of reliability P=95%.

From the performed analysis using Taguchi optimization method it was concluded that the use of a higher gas pressure combined with a low feed-rate have an important role in lowering the Rz values for the surface roughness.

The model resulted can be used for obtaining the optimum values for feed and gas pressure regarding the surface roughness in the case of a mild steel S355JR 10mm cut with laser.

It was also concluded that the optimization of the cutting parameters is a technique that improves the surface quality in terms of surface roughness, [1].

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