EXPERIMENTAL ANALYSIS AND OPTIMIZATION OF CO_2 LASER CUTTING PROCESS FOR STAINLESS STEEL USING DESIGN OF EXPERIMENTS (DOE)

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Abstract: Samples of stainless steel X5CrNi*18*10 (1.4301) with thickness 3mm were cut on a CO_2 laser cutting system Mazak Super Turbo-X 48 Mk2 1800 W using O_2 as assisting gas and the combined effects of the gas pressure, power, frequency, efficiency and feed rate on surface roughness have been studied. The study was conducted in an operational manufacturing environment and was based on the design of a 2^5 full factorial experiment. It was observed that feed rate and efficiency had a major effect on roughness variation. Using DOE a complex relationship to show roughness R_z variation according to these parameters was find. DOE allows to separate the most important factors affecting the cutting process, to clarify their interaction to reduce the total number of sets of parameters that must be examined and also identify parameters that can be optimized. The results show the ability of DOE to optimize laser cutting processes.

1. INTRODUCTION

Laser cutting is a fairly new technology that allows metals to be cut with extreme precision if required. The laser beam is typically 0.2 mm in diameter with a power of 1-2 kW. Depending on the application of the laser cutter a selection of different gases are used in conjunction with the cutting.

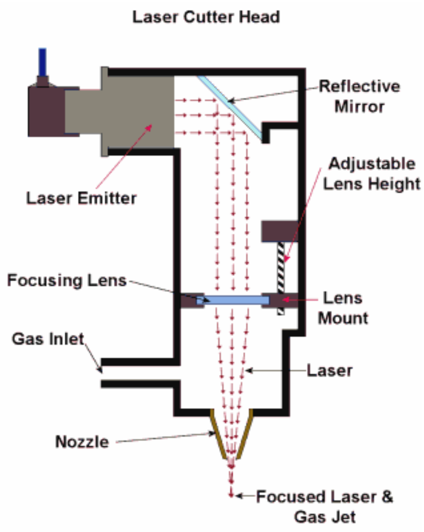


Figure 1. Laser system

Laser cutting is divided into three processes: oxygen cutting, nitrogen cutting and sublimation cutting. When cutting with oxygen, material is burned and vaporized when heated by the laser beam to ignition temperature. The reaction between the oxygen and the metal creates additional energy in the form of heat, supporting the cutting process. These exothermic reactions explain why oxygen can penetrate thick and reflective material; however, they need to be controlled, since violent reactions can occur and not only reduce cut quality but affect workplace safety.

Laser cutting for shaping and separating work pieces into parts of desired geometry is one of the most widespread tasks of laser material processing. For certain well defined applications, e.g. cutting metal sheet using CO_2-lasers, suppliers of laser cutting machines provide a comprehensive database for process parameters. However, in general new customized cutting processes have to be Figure 1**,** individually optimized with respect to the targeted geometry and the material to be cut while taking into account the equipment to be used. Since laser cutting processes are often governed by a multitude of parameters, some of which interacting with each other, the optimization of a process is determined by a high degree of complexity, [1]. As a consequence, the optimization of an industrial laser process might be a time consuming and cost intensive task, particularly in case simplified methods such as the one-factor at a time approach are applied. In addition, possible interactions of different factors might

remain partly unconsidered if such intuitive approaches are chosen. In this paper, we present an optimization study of laser cutting of stainless steel using a design of experiments.
The purpose of the paper is to find a model using DOE based also on the influence of the laser parameters to the output parameter Rz. This study was realized on a laser system Mazak Super Turbo-X 48 Mk2 1800 W CO_2, figure 2, to cut stainless steel with thickness 3 mm using O_2 as assisting gas.

Figure 2. Laser system Mazak Super Turbo-X 48 Mk2 1800W

Figure 3. Roughness measuring equipment

To investigate the influence of roughness a model has been created for dependence upon the cutting parameters. Attempts to measure surface roughness were performed on work-piece of stainless steel X5CrNi*18*10 (1.4301), 1250x2500x6. The measured parameter of surface roughness were Rz, [4] in µm and was measured on a Mitutoyo SV-C 600 measuring tool and Surfpak-SV 1.500 software for analyse, figure 3.

2. EXPERIMENTAL TESTS

A series of experiments have been performed under the experimental plan to analyze the influence of the process parameters on roughness parameters and to obtain a complex relationship to show roughness variation according to these parameters.

The experimental tests were based on 2^5 factorial plan. Such experiments or studies are called factorial experiments because we are interested in the effects of two or more factors on the response variable.

In factorial experiments, the data can be split into sub-samples corresponding to each possible combination of levels of the different factors. The effects of the factors can be analyzed by comparing the different sub-samples appropriately. In this section, we introduce some terminology and define a model for factorial experiments.

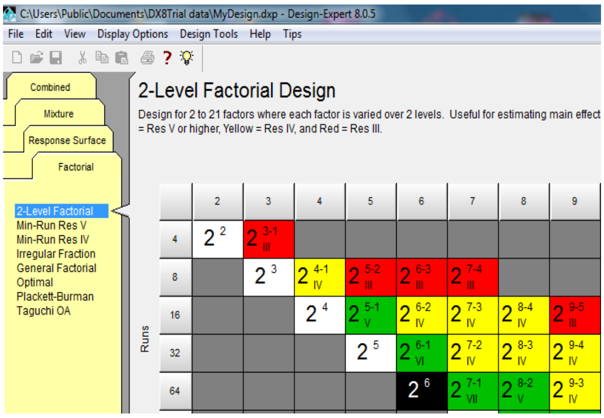
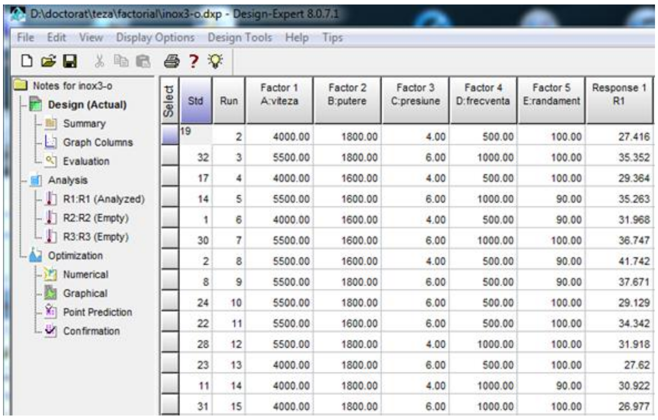


Figure 4. The design of the experiment



Std	Run	Factor 1 A:viteza	Factor 2 B:putere	Factor 3 C:presiune	Factor 4 D:frecventa	Factor 5 E:randament	Response 1 R1
19	2	4000.00	1800.00	4.00	500.00	100.00	27.416
32	3	5500.00	1800.00	6.00	1000.00	100.00	35.352
17	4	4000.00	1600.00	4.00	500.00	100.00	29.364
14	5	5500.00	1600.00	6.00	1000.00	90.00	35.263
1	6	4000.00	1600.00	4.00	500.00	90.00	31.968
30	7	5500.00	1600.00	6.00	1000.00	100.00	36.747
2	8	5500.00	1600.00	4.00	500.00	90.00	41.742
8	9	5500.00	1800.00	6.00	500.00	90.00	37.671
24	10	5500.00	1800.00	6.00	500.00	100.00	29.129
22	11	5500.00	1600.00	6.00	500.00	100.00	34.342
28	12	5500.00	1800.00	4.00	1000.00	100.00	31.918
23	13	4000.00	1800.00	6.00	500.00	100.00	27.62
11	14	4000.00	1800.00	4.00	1000.00	90.00	30.922
31	15	4000.00	1800.00	6.00	1000.00	100.00	26.977

Figure 5. 2^5 factorial plan

For obtaining the mathematical model of the experimental results obtained an experiment 2^5 plan was performed using the software Design – Expert, figure 4. In figure 5 the factorial plan and the results are presents.

Design of Experiments (DOE) techniques for studying the factors that may affect a product or process in order to identify significant factors and optimize designs. The software also expands upon standard methods to provide the proper analysis treatment for interval and right censored data - offering a major breakthrough for reliability-related analyses. To find the factors with the biggest influence above the output parameter was used the Pareto chart, figure 6. To find the model and study the influence factors was used an factorial model with response Rz and was ignored the 3FI interactions, figure 7.

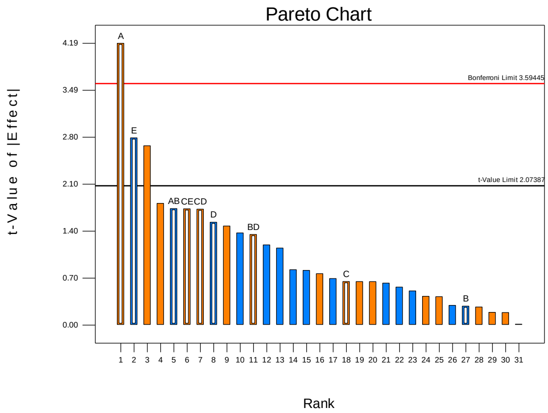


Figure 6. Pareto chart

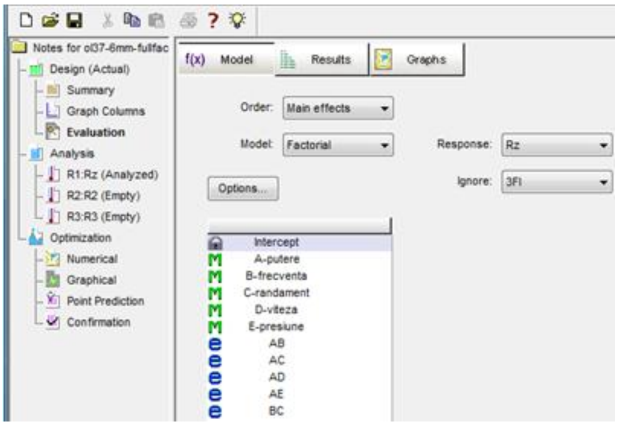


Figure 7. Model choice

Introducing the experimental data in the software the recommended regression model that matched the data was the polynomial regression. Thus, the following equation was derived by the software:

- coded factors:

$$R_z = 31.22 + 3.6 \cdot A - 0.24 \cdot B + 0.56 \cdot C - 1.32 \cdot D - 2.39 \cdot E - 1.49 \cdot A \cdot B + \\ + 1.16 \cdot B \cdot D + 1.48 \cdot C \cdot D + 1.49 \cdot C \cdot E \quad (1.1)$$

- actual factors:

$$R_Z = +121{,}41908 + 0.038578 \cdot velocity + 0.057161 \cdot power - 32.15022 \cdot presure -$$
$$- 0{,}11374 \cdot frequency - 1.96634 \cdot efficiency - 1.98654 \cdot vellocity \cdot power +$$
$$+ 4.63662 \cdot power \cdot frequency + 5.93037 \cdot presure \cdot frequency +$$
$$+ 0.29747 \cdot presure \cdot efficiency \qquad (1.2)$$

Applying the ANOVA analyze on the roughness model derived we can obtain the influence of each parameter and the adequacy of the model. The summary of the analyze is shown in table 1. The data correspond for a degree of reliability P= 95%, (α= 0.5) and the value of Fisher test shows that the model is significant and in this case feed rate and efficiency are significant model terms. In figure 8 and 9 there is represented the influence of the feed rate v [mm/min] and efficiency rate R [%] that are the most significant factors in this sequence.

Table 1

Response Rz						
ANOVA for selected factorial model						
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	921,7317073	9	102,4146341	4,331364215	**0.0024**	**significant**
A-velocity	415,8367508	1	415,8367508	17,58674858	**0.0004**	**significant**
B-power	1,881315031	1	1,881315031	0,079565393	0.7805	
C-pressure	9,931310281	1	9,931310281	0,42001929	0.5236	
D-frequency	55,37465703	1	55,37465703	2,34192906	0.1402	
E-efficiency	183,54801	1	183,54801	7,762692207	**0.0108**	**significant**
AB	71,03426028	1	71,03426028	3,004211806	0.0970	
BD	42,99658278	1	42,99658278	1,818430165	0.1912	
CD	70,33869528	1	70,33869528	2,974794669	0.0986	
CE	70,79012578	1	70,79012578	2,993886764	0.0976	
Residual	520,1875989	22	23,64489086			
Cor Total	1441,919306	31				

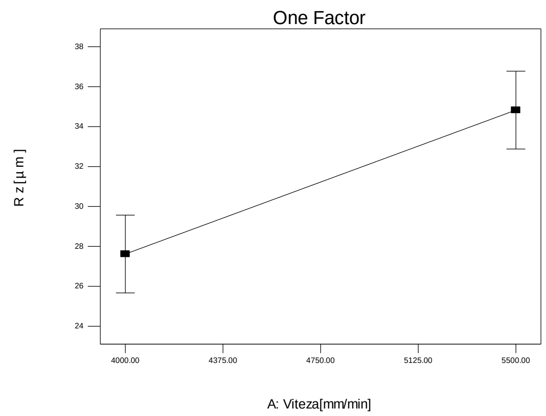


Figure 8. Feed rate influence on Rz

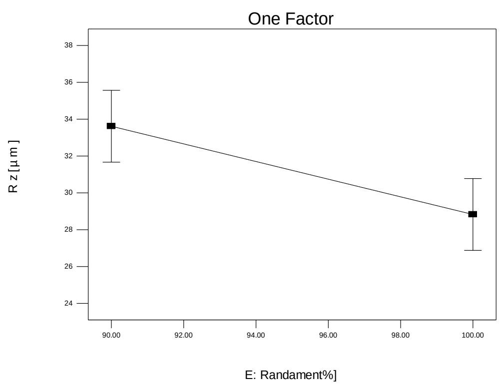


Figure 9. Efficiency influence on Rz

To reach a high profitability we need to increase the cutting speed and to reduce the gas pressure. Because of that we will optimized forward the cutting speed and gas pressure. In figure 10 there is represented the influence of the feed rate and gas pressure to the surface roughness. We see that the gas pressure has no influence in surface roughness.

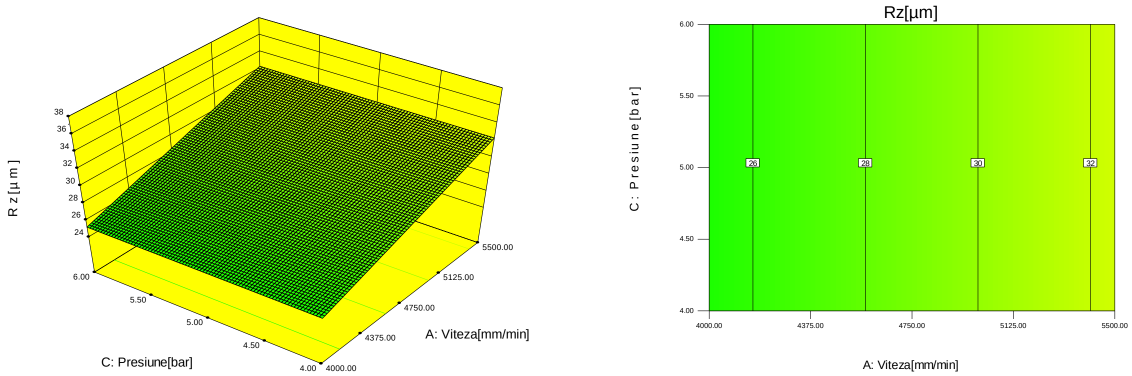


Figure 10. Feed rate and gas pressure influence on Rz

The next step was the optimization of factors for a minimum roughness. Also we choose a maximum feed rate and a minimum gas presure for a better profitability, figure 11.

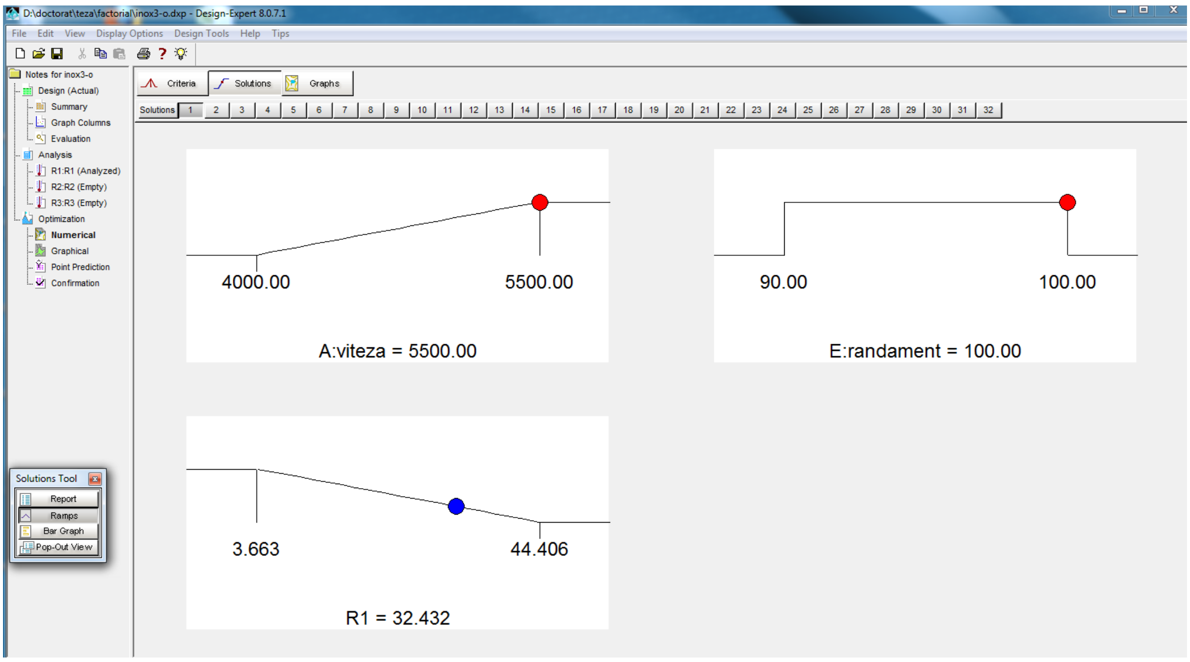


Figure 11. Numerical optimization

Based on the regression model we can adjust the process parameters in order to reach the minimum surface roughness while maintaining high feed rates, table 2.

Table 2

Number	Feed rate	Power	Gas pressure	Frequency	Efficiency	Rz
1	5500.00	1700.00	4.00	750.00	100.00	32.432

The optimization result is shown in figure 12 and we see that we get the better desirability for the model at maximum feed rate and minimum gas pressure.

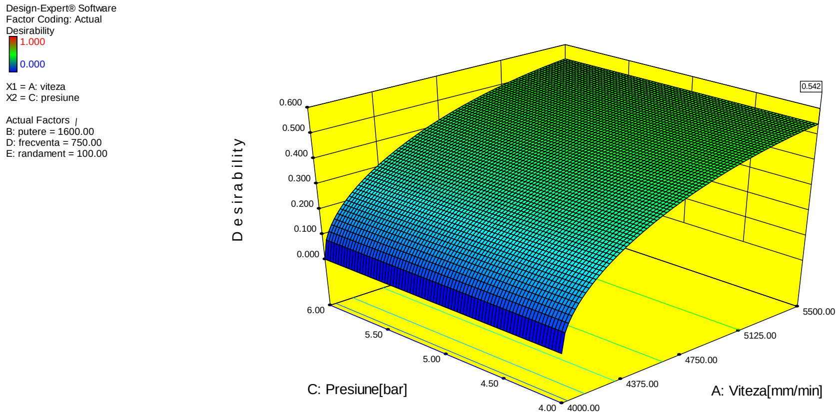


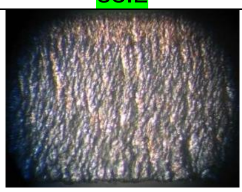
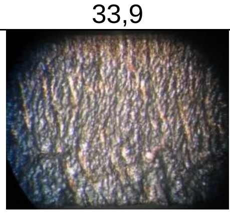
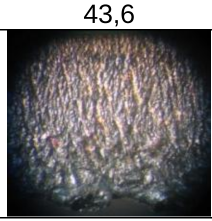
Figure 12. 3D Surface plot of Desirability

3. CONCLUSIONS

The main conclusions drawn from the paper are:

- The mathematical model derived from the experiment is significant;
- The ANOVA analyze performed assures the reliability of the models indicating a good significance of the factors at a degree of reliability P = 95%;
- With this model we find an optimum settings for the input parameters, increase the cutting speed with about 30% while maintaining the roughness to a lower value. In table 3 there are shown 3 photos at three cutting speed: 4000 [mm/min] it is the initial cutting speed, 5500 [mm/min] it is the new optimized cutting speed and the 5800 [mm/min] it is a new test to a higher speed. We see dross attachement and burning damage in the bottom region of the workpiece at the speed of 5800 [mm/min]. This confirms us that our result is near to the maximum acceptable cutting speed.

Table 3

Piece Nr.	105	131	132
v[mm/min]	4000	5500	5800
Rz[μm]	33.2	33,9	43,6
Piece photo			

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