# SURFACE ROUGHNESS OPTIMIZATION IN $CO_2$ LASER CUTTING BY USING TAGUCHI METHOD

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*Lucrarea se referă la o modalitate de aplicare a metodei Taguchi în vederea optimizării rugozității suprafeței obținute la tăierea cu laser $CO_2$ a semifabricatelor din oțel moale. Cercetarea experimentală a fost concepută și s-a desfășurat pe baza unui tabel ortogonal standard, de tip $L_{25}$, în cazul căruia principalii parametri de tăiere au fost viteza, puterea fasciculului laser și presiunea gazului de protecție, cu valori pe cinci niveluri. Prin analiza valorilor medii și prin analiza varianței, au fost identificate valori adecvate pentru parametrii importanți ai procesului de tăiere. Rezultatele au arătat că viteza de așchiere și presiunea gazului ajutător sunt cei mai importanți factori care afectează rugozitatea suprafeței, în timp ce influența puterii fasciculului laser este mult mai mică.*

*This paper demonstrates the application of Taguchi method for optimization of surface roughness in $CO_2$ laser cutting of mild steel. The experiment was designed and carried out on the basis of standard $L_{25}$ Taguchi's orthogonal array in which three laser cutting parameters such as the cutting speed, laser power and assist gas pressure were arranged at five levels. From the analysis of mean values of variance, the significant laser cutting parameters were identified. The results showed that the cutting speed and assist gas pressure are the most significant parameters affecting the surface roughness, whereas the influence of the laser power is much smaller.*

**Keywords**: $CO_2$ laser cutting, Taguchi method, surface roughness.

## 1. Introduction

Laser cutting is a thermal-based advanced machining process in which the material is melted or evaporated by focusing the laser beam on the workpiece surface. As a noncontact process it is an effective method of cutting a wide range of materials with a high degree of accuracy. Different types of lasers are available in the market such as solid lasers, liquid lasers and gaseous lasers. Nd:YAG and

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$CO_2$ are the two most widely used industrial lasers [1, 2]. The technological improvements in laser machines made laser cutting technology more prevalent in today's production systems. To maintain a high production rate and an acceptable level of cut quality, it is important to select the optimum combination of process parameters [3]. With a limited theoretical and practical background to assist in systematical selection, these parameters are usually set by previous experience, manufacturer recommendations or are set in time and cost expensive trial and error procedure. Above all, optimal cutting parameter settings for achieving good cut quality are not guaranteed. A number of researchers performed theoretical as well as experimental investigations in order to examine the laser cutting process. Studies that focused on the development and applications of laser beam cutting techniques were reviewed in [4]. When the cut quality is considered, in most reported studies, kerf width, surface roughness and heat affected zone, were commonly used as cut quality characteristics [5, 6].

Predictive modeling is essential for better understanding and optimization of the laser cutting process. Different methodologies were employed for modeling of laser cutting, such as analytical methods, statistical experimental methods and artificial intelligence based methods such as artificial neural networks and fuzzy logic. These methods are powerful tools for systematic modeling, analysis and optimization of cutting processes. However, they are more time and computationally expensive and require a considerable knowledge in mathematical modeling and optimization as well as artificial intelligence.

To overcome these problems, researches applied Taguchi method (TM) which provides a systematic, efficient and easy-to-use approach for the process optimization. The application of TM without formulation of any kind of model is an attractive alternative for determining of near optimal laser cutting parameter settings and is particularly popular when dealing with multiple-performance. Considerable research studies were carried out to improve the performance of laser cutting process previously with the use of TM [1, 2, 3, 7]. Reviewing the literature it was found that most of the experimental studies applied TM for optimization of single, but preferably multi-quality characteristics by coupling Taguchi method with the grey relational analysis. The open literature reveals that most of the applications of the Taguchi method consider optimization of kerf quality characteristics, material removal rate and surface roughness in Nd:YAG laser cutting.

This paper presents the application of the TM for determining of the optimal laser cutting parameter settings which minimize surface roughness in $CO_2$ laser cutting of S355J2G3 (EN) mild steel. Three laser cutting parameters such as cutting speed, laser power and assist gas pressure were considered in the experiment. The laser cutting experiment was planned and conducted according to the Taguchi's experimental design using the $L_{25}$ orthogonal array.

## 2. Experimental details

The laser cutting experiment was performed by means of ByVention 3015 (Bystronic) $CO_2$ laser, delivering a maximum output power of 2.2 kW at a wavelength of 10.6 µm, operating in CW mode. The cuts were performed with a Gaussian distribution beam mode ($TEM_{00}$) on 2 mm thick S355J2G3 (EN) mild steel using the oxygen as assist gas with purity of 99.95%. In consideration of the numerous parameters that influence cutting process and finally cut quality i.e. surface roughness, some of the process parameters were kept constant through the experimentation. A focusing lens with a focal length of 5 in. (127 mm) was used to perform the cut. The conical shape nozzle (HK10) with nozzle diameter of 1 mm was used. The nozzle–work piece stand-off distance was controlled at 0.7 mm. On the other hand, the main cutting parameters such as cutting speed ($v$), laser power ($P$) and assist gas pressure ($p$) were taken as variable input parameters. To cover wider range of laser cutting parameters that are controlled by the operator, these parameters were varied on 5 levels about 40% above and below their nominal operating level as recommended by the machine manufacturer (Table 1).

*Table 1*

**Laser cutting parameters and their levels**

| Laser cutting parameters | Unit | Level | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| Cutting speed, $v$ | m/min | 3 | 4 | 5 | 6 | 7 |
| Laser power, $P$ | kW | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 |
| Assist gas pressure, $p$ | bar | 3 | 4 | 5 | 6 | 7 |

Based on the selected laser cutting parameters and their levels, a design matrix was constructed in accordance with the standard $L_{25}$ Taguchi OA. The experimental results are summarized in Table 2.

Because of its impact on several functional attributes and overall performance of end product, surface roughness in laser cutting is of great importance. Roughness can be evaluated in many ways, the most used being as follows [8]: arithmetical average depth of the profile, symbolized by $R_a$ and average depth of roughness in 10 points, symbolized by $R_z$. To ascertain surface roughness straight cuts each of 60 mm in length were made in each experimental trial. $R_a$ and $R_z$ values on the cut edge were measured using Surftest SJ-301 (Mitutoyo) profilometer. Cut off length was 0.8 mm and evaluation length was 4 mm. Each measurement was taken along the cut at approximately the middle of the thickness and measurements were repeated three times to obtain averaged values (Table 2).

## 3. Taguchi method

Taguchi method (TM) is a powerful statistical technique for product/process quality improvement. This methodology aims at identifying optimal process parameter settings so as the variation in responses due to noise factors is nullified. Noise factors (external conditions, manufacturing imperfections, etc.) are unwanted sources of variation and can be uncontrollable

*Table 2*

**$L_{25}$ orthogonal array and surface roughness results**

| Trial | $v$ (m/min) | $P$ (kW) | $p$ (bar) | $R_a$ (μm) | $\eta$ (dB) | $R_z$ (μm) | $\eta$ (dB) |
|---|---|---|---|---|---|---|---|
| 1 | 3 | 0.7 | 3 | 1.487 | -3.4451 | 6.577 | -16.3678 |
| 2 | 3 | 0.9 | 4 | 1.290 | -2.2193 | 4.820 | -13.7523 |
| 3 | 3 | 1.1 | 5 | 2.073 | -6.3424 | 8.657 | -18.763 |
| 4 | 3 | 1.3 | 6 | 2.477 | -7.8847 | 9.030 | -19.1237 |
| 5 | 3 | 1.5 | 7 | 2.937 | -9.3818 | 11.070 | -20.9521 |
| 6 | 4 | 0.7 | 4 | 1.780 | -5.0227 | 8.073 | -18.1422 |
| 7 | 4 | 0.9 | 5 | 1.707 | -4.6502 | 7.647 | -17.6709 |
| 8 | 4 | 1.1 | 6 | 2.337 | -7.4065 | 9.483 | -19.5444 |
| 9 | 4 | 1.3 | 7 | 3.307 | -10.391 | 11.823 | -21.4651 |
| 10 | 4 | 1.5 | 3 | 1.190 | -1.5338 | 4.210 | -12.5094 |
| 11 | 5 | 0.7 | 5 | 2.013 | -6.0977 | 7.807 | -17.8508 |
| 12 | 5 | 0.9 | 6 | 2.017 | -6.1078 | 8.223 | -18.3145 |
| 13 | 5 | 1.1 | 7 | 2.603 | -8.3172 | 9.600 | -19.6485 |
| 14 | 5 | 1.3 | 3 | 1.173 | -1.3919 | 4.287 | -12.6811 |
| 15 | 5 | 1.5 | 4 | 1.380 | -2.8431 | 5.443 | -14.7177 |
| 16 | 6 | 0.7 | 6 | 1.660 | -4.4193 | 6.277 | -15.9578 |
| 17 | 6 | 0.9 | 7 | 1.710 | -4.6793 | 6.417 | -16.1471 |
| 18 | 6 | 1.1 | 3 | 0.963 | 0.2269 | 3.633 | -11.2363 |
| 19 | 6 | 1.3 | 4 | 1.007 | -0.0886 | 3.603 | -11.1426 |
| 20 | 6 | 1.5 | 5 | 1.143 | -1.2347 | 4.530 | -13.2714 |
| 21 | 7 | 0.7 | 7 | 1.587 | -4.0126 | 5.977 | -15.5448 |
| **22** | **7** | **0.9** | **3** | **0.832** | **2.4367** | **2.757** | **-8.83065** |
| 23 | 7 | 1.1 | 4 | 0.903 | 0.8195 | 3.220 | -10.2448 |
| 24 | 7 | 1.3 | 5 | 0.88 | 2.1481 | 2.700 | -8.66181 |
| 25 | 7 | 1.5 | 6 | 1.073 | -0.7547 | 4.267 | -12.7334 |

or too expensive to control. Two major tools used in Taguchi optimization methodology are orthogonal arrays (OAs), and signal to noise (S/N) ratio [9]. An OA is a small fraction of full factorial design and assures a balanced comparison of levels of any factor or interaction of factors. The columns of an OA represent the experimental parameters to be optimized and the rows represent the individual trials (combinations of levels). The array is called *orthogonal* because for every pair of parameters, all combinations of parameter levels occur an equal number of times. The mean and the variance of the response at each setting of parameters in OA are then combined into a single performance measure known as S/N ratio [7]. Taguchi found out empirically that S/N ratios give the (near) optimal combination of the parameter levels, where the variance is minimum, while keeping the mean close to the target value [10]. Depending on the criterion for the quality characteristic to be optimized, different S/N ratios can be chosen: smaller-the-better, larger-the-better, and nominal-the-best.

Regardless of the category of the performance characteristic, the larger algebraic value of S/N ratio corresponds to the better performance characteristic, and hence the optimal level of the parameter is the level with the highest S/N. In Taguchi method, optimal parameter levels are usually determined using the analysis of means (ANOM). ANOM is a statistical approach of estimating the mean S/N ratios for each parameter and each of its levels. However, when there are significant interactions between factors, the optimal parameter levels are more accurately determined using the analysis of variance (ANOVA) and by considering the interaction plots.

## 4. Results and discussion

In the present paper, Taguchi method was used to identify the optimal laser cutting parameter levels so as to minimize the surface roughness. In $CO_2$ laser cutting process, lower values of the surface roughness are desirable for maintaining high cut quality, therefore smaller-the-better S/N ratio can be calculated as:

$$S / N \equiv \eta = -10\, log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

where $y_i$ is the $i$-th observed value of the response, and $n$ is the number of observations in a trial. The experimental results were analyzed with ANOM and ANOVA. The analyses have been obtained by using the statistical software MINITAB. The calculations of ANOM and ANOVA are described in detail in [9, 11].

On the basis of data given in Table 2, the effects of the laser cutting parameters on mean S/N ratio are presented in graphical form (Figure 1).

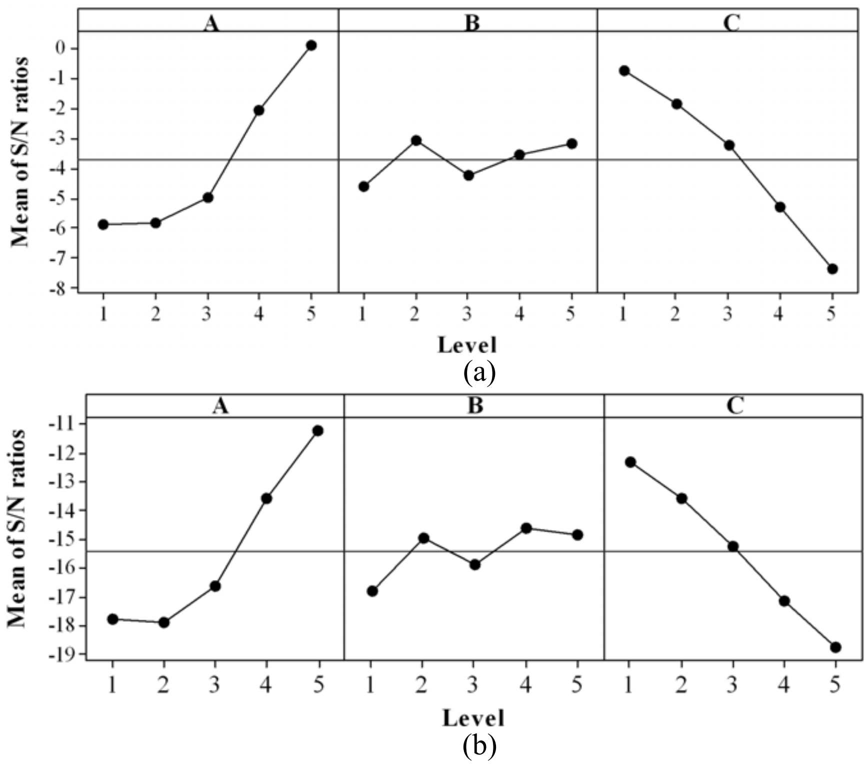



Fig. 1. Main effects plot for S/N ratios: (a) for $R_a$; (b) for $R_z$

The response graphs show the change in the response when a given factor goes from lower level to higher level. The slope of the line determines the power of the control factors influence on surface roughness. Graphs from Figure 1 clearly suggest a dominant influence, in a quantitative sense, of the cutting speed and assist gas pressure on the surface roughness. The effect of the cutting speed can be explained by the fact that as the cutting speed increases, the interaction time between the laser beam and material decreases, i.e. the heat generation decreases which leads to minimum side burning. By an increase in the assist gas pressure, the heat generated by the exothermic reaction is increased, which results in self-burning of the cut surface and hence increase in the surface roughness. From the Fig. 1, one can observe that the optimal combination of laser cutting parameter levels is $A_5B_2C_1$. In other words, using cutting speed of 7 m/min at laser power of 0.9 kW and by using assist gas pressure of 3 bar is beneficial for surface roughness minimization.

However, to find the relative contribution of each laser cutting parameter on the surface roughness and confirm initial assumption of the optimal conditions, the statistical analysis through ANOVA was performed. The ANOVA results for S/N ratio are shown in Tables 3 and 4.

*Table 3*

**ANOVA for S/N ratio (for $R_a$)**

| Source of variation | DOF | Sum of squares | Mean square | F | δ (%) |
|---|---|---|---|---|---|
| A | 4 | 140.152 | 35.038 | 41.45 | 46.58 |
| B | 4 | 9.140 | 2.285 | 2.70 | 3.04 |
| C | 4 | 141.456 | 35.364 | 41.84 | 47.01 |
| Error | 12 | 10.143 | 0.845 | | 3.37 |
| Total | 24 | 300.892 | | | |

*Table 4*

**ANOVA for S/N ratio (for $R_z$)**

| Source of variation | DOF | Sum of squares | Mean square | F | δ (%) |
|---|---|---|---|---|---|
| A | 4 | 171.898 | 42.975 | 34.02 | 50.83 |
| B | 4 | 16.318 | 4.080 | 3.23 | 4.83 |
| C | 4 | 134.808 | 33.702 | 26.68 | 39.86 |
| Error | 12 | 15.158 | 1.263 | | 4.48 |
| Total | 24 | 338.182 | | | |

In ANOVA, the ratio between the variance of the cutting parameter and the error variance is called Fisher's ratio ($F$). It is used to determine whether the parameter has a significant effect on the quality characteristic by comparing the $F$ test value of the parameter with the standard $F$ table value ($F_\alpha$) at the α significance level. If the $F$ test value is greater than $F_\alpha$, the cutting parameter is considered significant. The ANOVA results indicate that the cutting speed and assist gas pressure are statistically significant at the 99% confidence level ($\alpha$=0.01), whereas the effect of the laser power is statistically significant at the 90% confidence level ($\alpha$=0.1). The percent contribution of source to the total variation defines parameter sensitivity. It can be seen from Tables 2 and 3 that changing the design parameters levels of A, B and C contributes to about 96 % of the total variation in surface roughness. The small percent contribution of error confirms the absence of significant parameter interactions. Therefore, it is not necessary to perform the revision of the original solution to the optimal arrangement of parameter levels ($A_5B_2C_1$).

Confirmation testing is necessary and important step in the Taguchi method. Once the optimal combination of cutting parameters is selected, the final step is to predict and verify the expected response through the confirmation test. Since the optimal combination ($A_5B_2C_1$) corresponds to the 22-nd trial in the OA, no confirmation experiment trials were conducted. Taguchi prediction of S/N ratio under optimum conditions can be calculated as [9]:

$$\hat{\eta}_{opt} = \overline{\eta} + \sum_{i=1}^{p}(\overline{\eta}_{i,opt} - \overline{\eta}) \tag{2}$$

where $\overline{\eta}_{i,opt}$ is the mean S/N ratio for $i$-th parameter at the optimal level, $p$ is the number of parameters that significantly affect the quality characteristic.

Using Eq. 2 Taguchi predictions of S/N ratio under optimum conditions are $\eta_{obs} = 3.74947$ for $R_a$ and $\eta_{obs} = -7.63729$ for $R_z$. In order to statistically judge the closeness of the predicted ($\hat{\eta}_{opt}$) and observed value of S/N ratio ($\eta_{obs}$), the confidence intervals (CIs) values of $\hat{\eta}_{opt}$ for the optimal parameter level combination at 95% confidence band are determined. The CI is given by [11]:

$$CI = \sqrt{F_{(1,f_e)} \cdot V_e\left[\frac{1}{n} + \frac{1}{n_{ver}}\right]} \tag{3}$$

where $F_{(1;fe)}$ is the $F$ value from statistic table at a 95 % confidence level, $f_e$ is the degrees of freedom for the error, $V_e$ is the mean square of error, $n_{ver}$=3 is the validation test trial number, and $n$ is defined as:

$$n = \frac{N}{1+\nu} \tag{4}$$

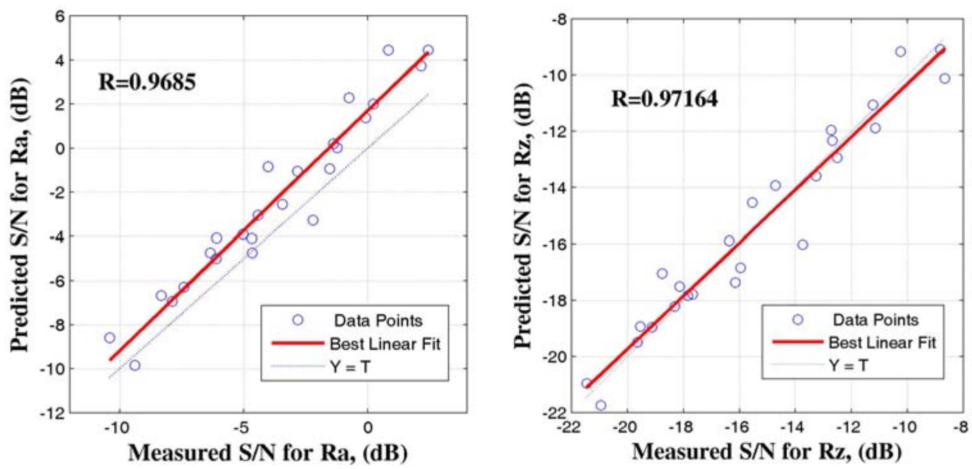
where $N$=25 is the total number of experiments and $\nu$=12 is the total degrees of freedom of all parameters.

If the difference between $\hat{\eta}_{opt}$ and $\eta_{obs}$ is within the CI value, then the optimum laser cutting parameter level combinations are valid. At the 95% confidence level, the CI is ±2.462 for the $R_a$ and ±3.010 for the $R_z$. Since the prediction errors are within CI values the optimal combination of laser cutting parameter levels can be validated.

In some cases, for technical-technological reasons, it is not possible to use the optimal values of cutting parameters, for the chosen optimization criteria. The selected quality characteristic may be determined in an indirect way from the multiple regression equation, which establishes the dependency between the corresponding category of S/N ratio and the laser cutting parameters. In this case, from data in Table 2, the following equations were obtained:

$$\begin{aligned}
\eta_{R_a} &= 2.48 - 4.28v + 12P - 1.22p + 0.449v^2 - \\
&- 4.47P^2 - 0.186p^2 - 0.048vP + 0.283vp \\
\eta_{R_z} &= -15.7 - 3.8v + 23.2P - 1.88p + 0.479v^2 - \\
&- 7.42P^2 - 0.146p^2 - 0.79vP + 0.324vp
\end{aligned} \tag{5}$$

In the present study, the parameters in Eq. 5 were estimated by the method of least-squares. Fig. 2 shows good agreement of the results obtained by using Eq. 5 and the results given in Table 2.




(a) (b)

Fig. 2. Comparison of measured and predicted values of S/N ratio for: (a) $R_a$, and (b) $R_z$

The surface roughness values can be then determined from the simple relation:

$$\begin{aligned}
R_a &= 10^{-\frac{\eta_{Ra}}{20}} \\
R_z &= 10^{-\frac{\eta_{Rz}}{20}}
\end{aligned} \tag{6}$$

Thus, using Eqs. 5 and 6 one can determine surface roughness values for arbitrarily chosen values of the laser cutting parameters.

## 5. Conclusions

This paper presents the Taguchi method for optimization of surface roughness in $CO_2$ laser cutting of mild steel using oxygen as assist gas. Three laser cutting parameters, cutting speed, laser power and assist gas pressure were considered in the experiment that was planned according to the Taguchi's experimental design by using $L_{25}$ orthogonal array. From the experimental results and derived analysis, the following conclusions can be drawn:

- cutting speed and assist gas pressure are the most significant parameters affecting the surface roughness variation, whereas the influence of the laser power is much smaller,
- the ANOVA resulted in less than 5% error indicating that the interaction effects of the laser cutting parameters are negligible,
- it was observed that the cutting speed should be kept at the highest level (7 m/min), assist gas pressure at the lowest level (3 bar), while laser power should be kept at an intermediate level (0.9 kW) for obtaining minimal surface roughness,
- through the developed mathematical models, any experimental results of surface roughness with any combination of laser cutting parameters can be estimated.

## R E F E R E N C E S

[1]. *A.K. Pandey*, *A.K. Dubey*, Taguchi Based Fuzzy Logic Optimization of Multiple Quality Characteristics in Laser Cutting of Duralumin Sheet, Optics and Lasers in Engineering, vol. 50, no. 3, 2012, pp. 328–335.

[2]. *A. Sharma, V. Yadava*, Modelling and Optimization of Cut Quality During Pulsed Nd:YAG Laser Cutting of Thin Al-Alloy Sheet for Straight Profile, Optics and Laser Technology, vol. 44, no. 1, 2012, pp. 159–168.

[3]. *U. Caydaş, A. Hasçalik*, Use of the Grey Relational Analysis to Determine Optimum Laser Cutting Parameters with Multi-Performance Characteristics, Optics and Laser Technology, vol. 40, no. 7, 2008, pp. 987–994.

[4]. *A.K. Dubey, V. Yadava,* Laser Beam Machining - A Review, International Journal of Machine Tools and Manufacture, vol. 48, no. 6, 2008, pp. 609–628.

[5]. *M. Radovanović, M. Madić*, Experimental Investigations of $CO_2$ Laser Cut Quality: A Review, Nonconventional Technologies Review, vol. 15, no. 4, 2011, pp. 35–42.

[6]. *L. Slătineanu, M. Coteaţă, I. Beşliu, O. Dodun,* Thermal Phenomena at the Laser Beam Machining, International Journal of Material Forming, 2010, vol. 3, suppl. 1, 2010, pp. 1103-1106.

[7]. *A.K. Dubey, V. Yadava*, Multi-Objective Optimization of Nd:YAG Laser Cutting of Nickel-Based Superalloy Sheet Using Orthogonal Array with Principal Component Analysis, Optics and Lasers in Engineering, vol. 46, no. 2, 2008, pp. 124–132.

[8]. *I. Călinescu, S.M. Croitoru*, *C. Minciu*, Surface roughness at milling zinc alloys, UPB Scientific Bulletin, Series D: Mechanical Engineering, vol. 72, no. 3, 2010, pp. 89–96.

[9]. *M.S. Phadke*, Quality Engineering Using Robust Design, Prentice Hall, New Jersey, 1989.

[10]. *V. Marinković, M. Madić*, Optimization of Surface Roughness in Turning Alloy Steel by Using Taguchi Method, Scientific Research and Essays, vol. 6, no. 16, 2011, pp. 3474–3484.

[11]. *P. Ross*, Taguchi Techniques for Quality Engineering, McGraw Hill, New York, 1988.