# OPTIMIZACIJA ELEMENATA REŽIMA OBRADE POMOĆU PLANIRANOG EKSPERIMENTA

# CUTTING CONDITIONS OPTIMIZATION BY MEANS OF DESIGN OF EXPERIMENT

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**REZIME**

*Postoji mnogo načina za ostvarivanje optimizacije procesa obrade. U eksperimentalnom dijelu ovog rada, optimizacija obrade je ostvarena s aspekta režima obrade kao nezavisnih varijabli (brzina, posmak i dubina), a zavisne varijable se odnose na hrapavost površine, tačnije, srednje aritmetičko odstupanje visina površine i rezultantne sile rezanja, koja se sastoji od glavne, posmične i sile prodiranja. Nakon što se formira matrica eksperimentalnog plana, na osnovu potpunog višefaktornog plana sa osam tačaka, sa prethodno utvrđenim donjim, srednjim i gornjim nivoom ulaznih režima rezanja struganja, pristupilo se eksperimentu.*
*Nakon što su dobijeni odgovarajući rezultati hrapavosti površine, koji su izmjereni pertometrom, kao i vrijednosti sila izmjerene dinamometrom, pristupilo se optimizaciji procesa obrade prethodno definiranim metodologijama, opisanim u ovom radu.*

***Conference paper***

**SUMMARY**

*There are many ways to accomplish optimization of machining process. In the experimental part of this paper, the optimization of machining process is accomplished from the aspect of cutting conditions, which are independent variables (speed, feed, and cutting depth), whereas the dependent variables refer to the surface roughness, more precisely, arithmetic average of surface heights and resultant cutting force, including main cutting force, feed force and thrust force. Once the matrix of the experimental plan has been created, on the basis of a complete multifactor plan with eight points, with previously determined upper, middle and lower levels of cutting parameters for turning, the experiment followed.*
*Once the results of surface roughness were measured by perthometer, as well as results of cutting forces by dynamometer, the optimization of machining process was treated by means of predetermined methodologies, described in this paper.*

## 1. INTRODUCTION

In contemporary manufacturing systems, the surface finish plays one of the most crucial roles when it comes to the characteristics of workpieces due to special requirements for specified surfaces that are to be machined upon a special request of customers. Naturally, not only the cutting parameters play a dominant role regarding quality of surface finish, but many other factors are responsible for it, such as machine stiffness, kinetic parameters, tool geometry, and so on. However, it is much easier to manipulate machining parameters, and this is why they play a crucial role in machining optimization and are mostly chosen for such activities. Optimization is very important when it comes to cutting technology and a lot of studies have been carried out for this purpose. It is important to mention that there are many methods that give us the possibility of optimization such as Taguchi method, Simplex method, Linear programming method, Method based on Sylvester's criteria, Genetic algorithmic approach, Approach based on Neural Networks and so on. In addition, some papers that covered named methods are given below. For example, in [2], the algorithmic approach for optimization of surface roughness is used.

This methodology allows to acquire the range of surface roughness values, and their corresponding optimum cutting conditions. In paper [3] is used Sylvester's criteria to obtain optimization of the percentage of lean to machining conditions and workpiece material microhardness. When it comes to papers [4, 7, 8, 9, 10], Taguchi method is used to obtain optimization. Regarding S/N ratio, they concluded the optimum point of experiment, in dependence of which approach is used. In every single quoted paper same methodology is used for optimization in various industrial environments and for various conditions regarding machining. Furthermore, in paper [5], neural networks (NN) are used and proper methodology with outcome optimization is shown. The feedforward NN and radial basis NN are used and based on available time for training and testing and by means of required accuracy, it is easy to choose proper NN. It is important to mention surface response methodology [11,12]. Based on the chosen design and determined values of input variables, optimal point or interval, where we can find optimum, can be obtained. In the light of the aforementioned facts, knowing a specific methodology for the purpose of achieving the best results in the shortest time possible is vital considering that manufacturing of products, as well as the time frame, have been shortened. Therefore, the pivotal role of technological-engineering in production is to specifically achieve such results of cutting parameters either in the shortest time frame possible or cost effective, or else obtain the required product of desired quality including both dimensions and shape, as well as the surface roughness.

## 2. DESIGN OF EXPERIMENT

Design of experiment (DOE) is powerful analysis tool for modeling and analyzing of the process effect. The application design of experiment is able to reduce the experiment expenses. The design of the experiment method is an effective approach to optimize the various cutting parameters of machining processes. The most commonly used terms in the DOE methodology include: controllable and uncontrollable input factors, responses, hypothesis testing, blocking, replication and interaction. Controllable input factors are those input parameters that are in complete control of the designer and can be modified during the process. Uncontrollable input factors are the parameters that cannot be changed or controlled by the designer. These factors need to be recognized to understand their effects on the responses, or output. The responses are the elements of the process outcome that gauge the desired effect. The controllable input factors can be altered, so as to optimize the output. The relationship between the factors and responses is shown in Figure 1. In the case of this paper, controllable input factors are cutting speed, feed and depth, cutting tool, conventional lathe and coolant. Output measures are surface roughness and cutting forces, while uncontrollable factors are, for instance, metallurgy and behavior of workpiece.

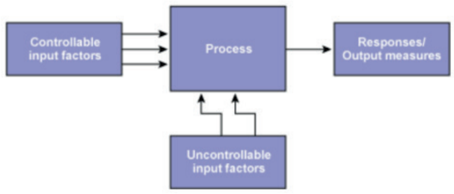


***Figure 1*** *Process Factors and Responses [13]*

In the turning process, these cutting parameters were selected as the independent input variables. The surface roughness and uses of cutting tool were assumed to be affected by the above three principal cutting parameters as the output responses.

### 2.1. The first case of gradient method

Optimal plans belong to the group of experimental plans and, therefore, rely on planned experiment theory, in which presence of regression analysis and proper methodology growingly conform with the first gradient method case, which has been used for optimization in this paper. Multifactorial linear regression is described by a formula below [1]:

$$\boldsymbol{Y} = \boldsymbol{b_o} + \sum_{i=1}^{k} \boldsymbol{b_i x_i} \tag{1}$$

$b_0$, $b_i$ – coefficients of regression

$x_i$ – input variables

$\lambda$ – parameter, calculated from relation:

$$\lambda = \frac{\mu}{|b_b|} \quad (2)$$

$b_b$ - coefficient regression value for which is $max(b_i w_i) \wedge 0 < \mu < 1$.

## 3. EXPERIMENTAL SETUP

Experimental research conditions include: cutting of all segments, performed by a mechanically fastened turning insert, serial number CNGA 120408T, where the cutting without cooling was performed on conventional *Potisje ADA* lathe, serial number MA50. The indicators of quality surface finish were measured by perthometer Mahr and, additionally, cutting forces were measured by means of dynamometer, as well. The workpiece material was made from constructional steel, serial number St 52-3 with diameter Ø52.

***Figure 2*** Potisje ADA *conventional lathe*

**Table 1** Mechanical and chemical properties of workpiece

| Material | Index | | | Ultimate strength | Modul of elasticity E | Poisson's ratio ν |
|---|---|---|---|---|---|---|
| | EN 10027-1 | DIN | JUS | | | |
| Structural steel | S355J2 | St 52-3 | Č.0562 | 490 | $2{,}1 \cdot 10^5$ | 0,3 |
| Chemical structure | C | | Si | Mn | P | S |
| | ≤ 0,24 | | ≤ 0,55 | ≤ 1,6 | ≤ 0,035 | ≤ 0,03 |

### 3.1. Cutting Conditions Optimization Using First Case of Gradient Method

The main goal of this research is to establish the optimal cutting parameters that result in minimum value of surface roughness based on the aforementioned methodology. Firstly, it is necessary to define a plan matrix. A full factorial plan of experiment with $2^3$ points without repetition will be used. The experiment plan matrix is shown in Table 2. It is important to pinpoint that relevant factors regarding output of surface roughness are, in fact, cutting parameters and, thus by varying them, the very experiment is accomplished. Once the plan matrix is established, it is necessary to determine the upper, middle and lower level of natural values that correspond with coded values from the matrix. Moreover, it is pivotal to ascertain an equal interval between the levels to continue the procedure.

**Table 2** Plan matrix of research

| Points | $x_0$ | $x_1$ | $x_2$ | $x_3$ | $v$ | $s$ | $a$ |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 150 | 0.196 | 1.5 |
| 2 | 1 | 1 | -1 | 1 | 150 | 0.05 | 1.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3 | 1 | -1 | -1 | 1 | 50 | 0.05 | 1.5 |
| 4 | 1 | -1 | -1 | -1 | 50 | 0.05 | 0,5 |
| 5 | 1 | 1 | 1 | -1 | 150 | 0.196 | 0.5 |
| 6 | 1 | 1 | -1 | -1 | 150 | 0.05 | 0.5 |
| 7 | 1 | -1 | 1 | -1 | 50 | 0.196 | 0.5 |
| 8 | 1 | -1 | 1 | 1 | 50 | 0.196 | 1.5 |

**Table 3** Results of experiment

| Points | $x_0$ | $x_1$ | $x_2$ | $x_3$ | $R_a$ |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1.39 |
| 2 | 1 | 1 | -1 | 1 | 1.118 |
| 3 | 1 | -1 | -1 | 1 | 1.799 |
| 4 | 1 | -1 | -1 | -1 | 2.324 |
| 5 | 1 | 1 | 1 | -1 | 1.415 |
| 6 | 1 | 1 | -1 | -1 | 0.774 |
| 7 | 1 | -1 | 1 | -1 | 4.105 |
| 8 | 1 | -1 | 1 | 1 | 1.825 |

Following the turning process done on lathe, the values of surface roughness have been measured by perthometer. The parameters of surface roughness on cylindrical workpieces have been measured on three points, precisely, every 120 degrees. Moreover, the mean value has been used for further calculations.

The table above plainly shows the minimum value of surface roughness has been acquired at sixth point by using maximum speed, minimum level of feed and minimum level of cutting depth. It is well known that with increasing of cutting speed comes increase of surface quality. Furthermore, cutting speed is a major factor for surface quality. According to the Microsoft Excel chart and Data Analysis features, a variance analysis (ANOVA) has been executed. Based on ANOVA analysis results, regression coefficients, as well as significance test, have been formed.

**Table 4** Regression statistics and ANOVA

| *Regression Statistics* | |
|---|---|
| Multiple R | 0,844548935 |
| R Square | 0,713262903 |
| Adjusted R Square | 0,498210081 |
| Standard Error | 0,728675682 |
| Observations | 8 |

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 3 | 5,2831665 | 1,7610555 | 3,316687015 | 0,138525203 |
| Residual | 4 | 2,123873 | 0,53096825 | | |
| Total | 7 | 7,4070395 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* |
|---|---|---|---|---|---|
| Intercept | 1,84375 | 0,257625758 | 7,156698978 | 0,002017367 | 1,128466225 |
| *v* | -0,6695 | 0,257625758 | -2,59873082 | 0,060128398 | -1,384783775 |
| *s* | 0,34 | 0,257625758 | 1,319743812 | 0,257384747 | -0,375283775 |
| *a* | -0,31075 | 0,257625758 | -1,20620702 | 0,29420054 | -1,026033775 |

According to the Student's test, it has been concluded that only speed parameter plays a significant role because:

$$t_{rač} = |-2{,}59874| > t_{n-2,\alpha=0{,}05} = 2{,}447 \quad (3)$$

while the first order model, in fact, encompasses both the effect of feed rate and depth of cut;

$$Y = b_o - b_1 \cdot v + b_2 \cdot s - b_3 \cdot a, \quad (4)$$

When the regression coefficients have been enlisted respectively:

$$Y = 1{,}8437 - 0{,}6695 \cdot v + 0{,}34 \cdot s - 0{,}311 \cdot a \quad (5)$$

Intervals of cutting parameters are:

$$w_1 = 50, w_2 = 0.071, w_3 = 0.5 \quad (6)$$

It is necessary to set interval multiplication and regression coefficients:

$$b_1 w_1 = -33{,}475 \quad (7)$$
$$b_2 w_2 = 0.02414$$
$$b_3 w_3 = -0.15538$$

Once the products have been established and the maximum influential product chosen, thus is $max\ (b_i w_i)$, in this case $b_1 w_1 = -33{,}475$.

Furthermore, with the determined maximum product, the regression coefficient corresponding to that product has been used to specify the parameter λ.

$$\mathbf{(0 \le \mu \le 1) - 0{,}8} \quad (8)$$

$$\boldsymbol{\lambda = \frac{0.8}{0.6695} = 1{,}194} \quad (9)$$

Afterwards, the step representing the product $\lambda b_i w_i$ has been specified as shown below:

$$\lambda |b_1 w_1| = 40$$
$$\lambda b_2 w_2 = 0.0288$$
$$\lambda |b_3 w_3| = 0.1856 \quad (10)$$

Given amounts are rounded and added to a basic natural value level of cutting parameters.

Moreover, the plan matrix is formed in natural coordinates. To obtain the output model, performing coding according to the D optimality in natural coordinates is mandatory.
Coding the factors is maintained according to the formula:

$$X_i = \frac{x_i - x_{oi}}{\frac{x_{imax} - x_{imin}}{2}} \quad (11)$$

Meaning:

$$x_{oi} = \frac{x_{max} + x_{min}}{2} - \text{mean value}$$
$$X_1 = \frac{x_1 - 100}{50} = 0.02x_1 - 2$$
$$X_2 = \frac{x_1 - 0.124}{0{,}071} = 14.08x_2 - 1.74 \quad (1)$$
$$X_3 = \frac{x_3 - 1}{0.5} = 2x_3 - 2$$

Obtained equations are inserted into the inital linear model resulting in the output equation for $R_a$.

$$Y = 3.21265 - 0.01339X_1 + 4.7879X_2 - 0.6125X_3 \quad (2)$$

A new chart containing six additional points, where speed and cutting depth ascend with obtained patch, whereas the feed descends, is formed. Such conditions seemingly contribute to the enhancement of surface finish.

**Table 5** New experimental points of the research and results of first two points after machining

| New points | $v$ | $s$ | $a$ | $n$ | $Y$ model | $s$ | $a$ | $N$ | $R_a$ |
|---|---|---|---|---|---|---|---|---|---|
| 9 | 140 | 0.095 | 1.2 | 856.98 | 1.047 | 0.098 | 1.2 | 910 | 1.087 |
| 10 | 180 | 0.066 | 1.4 | 1101.84 | 0.24 | 0.062 | 1.4 | 1100 | 0.873 |
| 11 | 220 | 0.037 | 1.6 | 1346.69 | -0.5 | | | | |
| 12 | 260 | 0.008 | 1.8 | 1591.54 | -1.3 | | | | |
| 13 | 300 | -0.021 | 2 | 1836.40 | -2.1 | | | | |
| 14 | 340 | -0.05 | 2.2 | 2081.25 | -2.9 | | | | |

Based on the obtained values of cutting parameters, machining is implemented with approximate cutting modes, as it is a stepped gear that can only achieve certain values.

Moreover, the negative values have been rejected and thus the initial two points have been processed. This indicates that increasing velocity effect is powerful to contribute to a nullification of the action referring to the free linear regression factor.

### 3.2. Example of Taguchi Method Optimization

During the experiment, cutting forces were measured by means of dynamometer Kistler and signals saved in the suitable Dynoware software. Mean values of three cutting forces were acquired and resultant forces for every point were calculated with the following formula:

$$F_R = \sqrt{F_1^2 + F_2^2 + F_3^2} \tag{3}$$

$F_1$ – the main cutting force

$F_2$ – feed force

$F_3$ – thrust force

**Table 6** Plan matrix of research with corresponding resultant cutting forces

| L8 | *v* | *s* | *a* | $F_{rez}$ | *S/N ratio* |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 98,20 | -39,8 |
| 2 | 1 | 1 | 2 | 343,61 | -50,7 |
| 3 | 1 | 2 | 1 | 227,42 | -47,1 |
| 4 | 1 | 2 | 2 | 1072,56 | -60,6 |
| 5 | 2 | 1 | 1 | 145,22 | -43,2 |
| 6 | 2 | 1 | 2 | 351,98 | -50,9 |
| 7 | 2 | 2 | 1 | 308,31 | -49,8 |
| 8 | 2 | 2 | 2 | 790,70 | -58 |

The data in the table above are adjusted to easily obtain input into the Minitab. Upper level is 2, and lower level in defined as 1. Taguchi method is a simple and efficient method for optimization approach. This uses two main tools signal to noise ratio and orthogonal array. Signal to noise ratio gives quality characteristic with respect to variation in process and orthogonal array adjusts many design factors in logical combination, which gives better results in less experimental runs and hence reduces time for experiment [7]. Taguchi experimental plan was used in the form of orthogonal arrays and linear graphs that give different combinations of parameters and their levels for each experiment. Based on this technique, the entire parameter space with the minimum number of experiments was used. This is a very powerful tool when the process is influenced by a large number of parameters. In Taguchi design, the choice of orthogonal arrays and appropriate linear graph are very important in order to draw valid conclusions after conduction of experimental runs. Table 6 shows Taguchi orthogonal arrays L8($2^7$); eight experimental runs with two levels of the each seven factors. Common L8 orthogonal array is given bellow.

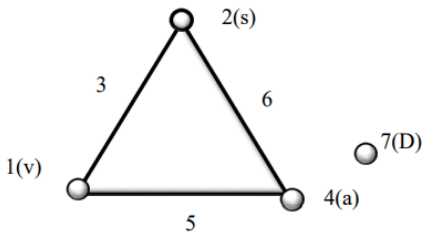


***Figure 4*** *Standard linear graph for L8 array [14]*

In this paper, *Smaller is better* approach is used. Besides, there are two other approaches: *Nominal is better* and *Larger is better*.

S/N ratio formula for *Smaller is better* approach is:

$$S/N_s = -10 \cdot \log\left(\frac{1}{r}\sum_{i=1}^{r} y_1^2\right) \tag{4}$$

Mean values for upper and lower levels are calculated in the table below based on the table 6. For example, for the lower level of cutting speed, first four rows are summed and divided by four. In the next chapter, following results and conclusions are given and it would be explained on which cutting condition levels would be obvious to expect optimal values of resultant cutting force.

Methodology for Taguchi optimization applied in this chapter of research paper is given bellow. In addition, Table 8 is created from the Table 6 as average of S/N ratios for upper and lower levels to determine the rank of significance.

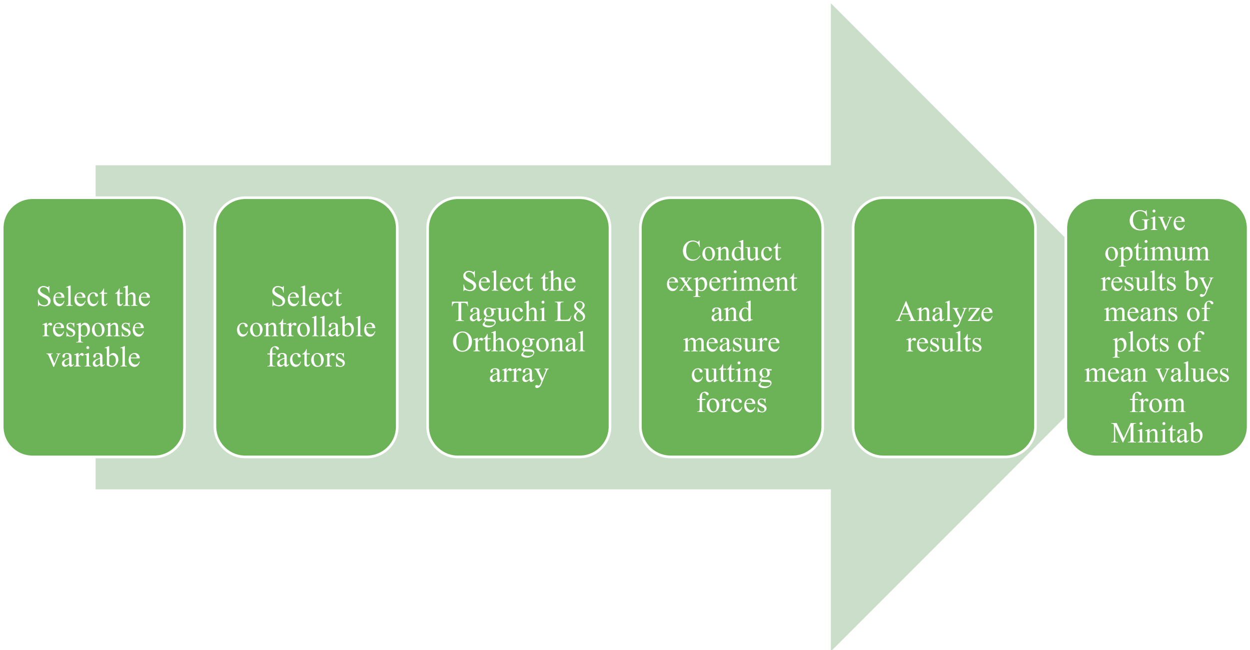


***Figure 3*** *Methodology for Taguchi optimization*

**Table 7** Mean values for upper and lower levels for cutting conditions and their interactions

| | *v* | *s* | *v·s* | *a* | *v·a* | *s·a* | *Error* |
|---|---|---|---|---|---|---|---|
| 1 | 435,45 | 234,75 | 385,20 | 194,79 | 367,07 | 526,67 | 457,76 |
| 2 | 399,05 | 599,75 | 449,29 | 639,71 | 467,42 | 307,83 | 376,74 |
| Δ | 36,39 | 364,99 | 64,08 | 444,92 | 100,34 | 218,83 | 81,02 |
| Rank | 7 | 2 | 6 | 1 | 4 | 3 | 5 |

**Table 8** S/N ratios for upper and lower levels and rank of significance for cutting conditions

| Level | *Speed [m/min]* | *Feed [mm/o]* | *Depth [mm]* |
|---|---|---|---|
| 1 | -49,5771 | -46,1836 | -44,9998 |
| 2 | -50,4777 | -53,8712 | -55,0551 |
| Δ | 0,900581 | 7,687639 | 10,05531 |
| Rank | 3 | 2 | 1 |

## 4. RESULTS AND DISCUSSION

**Table 9** Summary methodology and results of first case of gradient method

| Factors | $X_1(v)$ | $X_2(s)$ | $X_3(a)$ | $y$ | |
|---|---|---|---|---|---|
| Middle level $x_{oi}$ | 100 | 0.124 | 1 | | |
| Interval of variation $w_i$ | 50 | 0.071 | 0.5 | | |
| Upper level $x_{gi}$ | 150 | 0.196 | 1.5 | | |
| Lower level $x_{di}$ | 50 | 0.05 | 0.5 | | |
| Coded factors values | $x_1$ | $x_2$ | $x_3$ | $R_a$ | |
| 1 | +1 | +1 | +1 | 1.39 | |
| 2 | +1 | -1 | +1 | 1.118 | |
| 3 | -1 | -1 | +1 | 1.799 | |
| 4 | -1 | -1 | -1 | 2.324 | |
| 5 | +1 | +1 | -1 | 1.415 | |
| 6 | +1 | -1 | -1 | 0.774 | |
| 7 | -1 | +1 | -1 | 4.105 | |
| 8 | -1 | +1 | +1 | 1.825 | |
| Regression coefficients | $b_1$ $-0.6695$ | $b_2$ 0.34 | $b_3$ -0.31075 | | |
| $b_i w_i$ | -33.475 | 0.02414 | -0.155375 | | |
| $\lambda = \frac{\mu}{\lvert b_b \rvert} = \frac{0.8}{0.6695} =1.194922$ | | | | | |
| Pace $\lambda b_i w_i$ | 40 | 0.028845407 | 0.18566 | | |
| Rounded values: | 40 | 0.029 | 0.2 | | |
| New experimental points: | $X_1(v)$ | $X_2(s)$ | $X_3(a)$ | Linear model results | Experimenta l results |
| 9 | 140 | 0.095 | 1.2 | 1.047034 | 1.087 |
| 10 | 180 | 0.066 | 1.4 | 0.2483052 | 0.873 |

Therefore, the measured surface roughness results are presented in the table above, and in line with them, the conclusion is that the deviations of the cutting parameters and problems referring to the chip removal occur during machining at point 10. The optimization point is, in fact, the sixth point of the experiment, meaning all other values circulate around it. The difficulty regarding chip removal is important as striplined chip form appears. During the winding process revolving the workpiece, the striplined chip form is drawn under the knife and thus results in distortion of the surface finish integrity. On top of that, it can harm the operator. One of the problems due to conventional lathe was that how the speed increased, it also increased the interval between adjacent rounded speed value. So, it is the reason why experimental investigation required this speed values and interval, not only the highest that gives the lowest surface roughness. The model of linear regression for cutting regimes, implemented in this experiment, implies that by increasing the speed, value of surface roughness decreases. This fact is known from cutting theory and it is confirmed with given model of first-order linear regression. Due to these constrains, it was almost expected that the lowest value or the best surface finish is accomplished in first eight points.

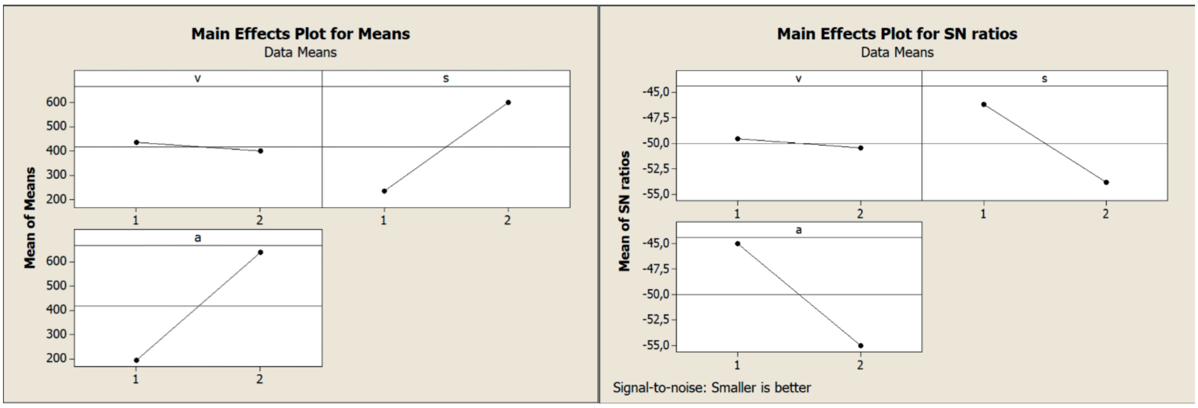


***Figure 5*** *Plots for SN ratios and means*

From the figures above, it is easy to conclude that both feed and cutting depth affect cutting forces. The cutting speed graph line is almost flat, so it cannot affect output values that much. Moreover, the smallest values for means and S/N ratios are obtained in the following levels: for speed it is level 2 (v = 150 m/min), for feed it is level 1 (s = 0,05 mm/rev) and for cutting depth it is level 1 (a = 1,5 mm), as well. Consequently, the smallest values of cutting forces are expected on these three levels of cutting conditions and further research can be continued from this point. Also, highest value of resultant cutting force can be expected with the lower level of cutting force, and upper levels of feed and depth. From Table 7 and Table 8, it is obvious that the highest impact has cutting depth and it is concluded by the rank of Δ. In addition, figures of the interaction of the input variables by means of S/N ratio and means are given bellow. Obviously, these patterns indicate that there is possibility only for interactions to be significant between speed – feed, feed – depth. It is required to check the p-value of the interaction term in the analysis of variance table.

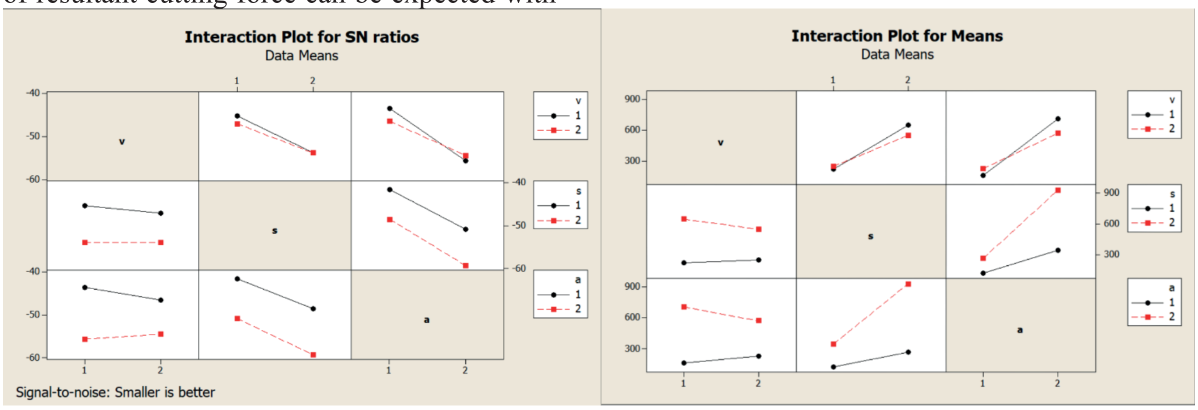


***Figure 6*** *Plots of input variables interactions*

## 5. CONCLUSION

This paper shows successful optimization of cutting conditions, even though optimization is not accomplished in additional points of experiment required, due to the used methodology. Optimization gives a very low value of surface roughness in sixth point of experiment that may be regarded as a optimum point. So, there is no need to go in further analysis and these results can be considered as valid. These results show us that by means of relevant methodology and with all constrains, it is possible to perform the optimization. This paper tackles one of the examples of optimization with experimental background, bringing out a very low roughness level, proving the very goal of the paper. Selecting appropriate values of cutting parameters and using some other items such as coolant led to the achievement of increasing of surface finish. In addition, Taguchi optimization method is accomplished, showing that this method represents a strong weapon to obtain optimal results quickly.

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