JOURNAL OF SCIENCE
SAKARYA UNIVERSITY

Sakarya University Journal of Science
ISSN 1301-4048 | e-ISSN 2147-835X | Period Bimonthly | Founded: 1997 | Publisher Sakarya University |
http://www.saujs.sakarya.edu.tr/

Title: Optimization of Surface Roughness of AISI 1040 Stainless Steel in Milling Process Using Taguchi Method

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Recieved: 2018-10-01 12:00:12

Revised: 2018-11-14 11:23:03

Accepted: 2018-12-13 10:05:04

Article Type: Research Article

Volume: 23

Issue: 1

Month: February

Year: 2019

Pages: 113-120

How to cite
Neslihan Özsoy, Murat Özsoy; (2019), Optimization of Surface Roughness of AISI 1040 Stainless Steel in Milling Process Using Taguchi Method. Sakarya University Journal of Science, 23(1), 113-120, DOI: 10.16984/saufenbilder.466053
Access link
http://www.saujs.sakarya.edu.tr/issue/38708/466053


Sakarya University Journal of Science 23(1), 113-120, 2019

# Optimization of Surface Roughness of AISI 1040 Stainless Steel in Milling Process Using Taguchi Method

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## ABSTRACT

Surface roughness significantly affects the work efficiency and life of machine parts interacting with each other. There are lots of parameters that affect surface roughness such as processed material, cutting tool, cutting parameters, cooling type. For this reason, optimization of the machining parameters and proper processing conditions are very important. In this study, the optimum machining conditions were determined by investigating the surface roughness of the milled AISI 1040 steel alloy depending on the feed per tooth (0.08 mm/tooth, 0.12 mm/tooth, 0.16 mm/tooth, 0.20 mm/tooth), spindle speed (2000 rpm, 3000 rpm, 40000 rpm, 5000 rpm) and the cooling type (liquid, air) parameters. The Taguchi experimental design method was used to help achieve results at acceptable levels and to save time and cost in achieving optimal results. Experiments designed with the Taguchi method were based on the L16 orthogonal array and signal / noise (S/N) ratios were used in the evaluation of the experimental results. The optimum levels of control factors for minimizing surface roughness were determined using S/N ratios. The ideal conditions of surface roughness were seen at A1B1C2 (i.e.,feed per tooth=0.08 mm/tooth and 2000 rpm spindle speed, cooling type=liquid). Variance analysis (ANOVA) was also conducted in the study. According to the results of analyses, it was found that spindle speed was the most dominant parameter for surface roughness. Lastly, confirmation tests were run to check the success of the optimization.

**Keywords:** Taguchi method, optimization, surface roughness, ANOVA, milling of stainless steel

## 1. INTRODUCTION

Due to the demand for more precise and complex products in the automotive, tooling and aerospace sectors, the increase in workability studies is taking place. Especially the flexibility of high-speed CNC machine tools, CAD/CAM software and the improvements in cutting tool technology show that the work in this area is dispersed in a very wide range.

AISI 1040 steel is widely used in the machinery and manufacturing industries and is used in a variety of machine parts, automotive parts, molds, fixtures and many other areas. Technological developments in the field of machining in recent years have led to many

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problems affecting machining performance, although machining makes machining more efficient.

The work in this area is focused on examining the cutting parameters (cutting speed, axial depth of cut, radial depth of cut and feed rate), cutting tool geometry/material and workpiece material changes on surface roughness. In the 1960s, the Taguchi method proposed by Genichi Taguchi is widely used due to its proven success in improving industrial product quality. The relevance to the "Taguchi" method of researchers is increasing day by day, especially because of the low number of experiments, ease of application and easy evaluation of qualitative variables.

Some studies on the subject:

Tosun et al. examined the surface roughness of AA7075-T6 using conventional and air cooling methods. They used a mixture of boron oil and water as the cutting process. They selected parameters as cutting tools, spindle speed and feed rates. As a result it was determined that the surface roughness increased when the feed rate increased and the surface roughness decreased when the spindle speed increased. [1].

Kahraman studied about optimizing cutting parameters to reduce surface roughness in turning of studs manufactured from AISI 5140 steel. She chose rotational speed, feed rate and depth of cut as control factors for the surface roughness and L9 orthogonal array for experiment trials. She considered rotational speed, feed rate and depth of cut as control factors for the surface roughness, and used L9 orthogonal array for experiment trials. She found optimal surface roughness as 1.70 µm according to S/N ratio analysis[2].

Kıvak experimented to investigate the machinability of hadfield steel with PVD TiAlN- and CVD TiCN/$Al_2O_3$-coated carbide inserts in dry milling conditions. He used the Taguchi method and regression analysis in his study. He selected cutting tool, cutting speed and feed rate as machining parameters. He obtained that feed rate had been the most effective parameter according to variance analysis [3].

Günay, AISI 316L austenitic stainless steel processing of the Fc and Ra cutting parameters and tool nose radius examined the optimization. He performed the experiments using Taguchi method [4].

Cakiroglu and Acir investigated drilling performance of Al2014 materials in dry cutting. They found out that cutting speed, feed rate and cutting tool had been effective on the performance [5].

In another study Debnath et all investigated effects of cutting speed, feed rate, depth of cut and cutting fluid conditions on surface roughness and tool wear in turning process of mild steel bar. They carried out experiments according to Taguchi's L9 orthogonal array and found that feed rate and the flow rate of the cutting fluid were the most effective parameters on surface roughness. On the other hand they explained that cutting speed and depth of cut were the dominant factors influencing tool wear [6].

Manivel and Gandhinatan optimized surface roughness and tool wear in hard turning of austempered ductile iron. They designed experiments by Taguchi method and selected cutting speed, feed rate and depth of cut as parameter [7].

Pillai et all conducted an experimental study of optimization of surface roughness and machining time in milling of Al6005A alloy. They used Taguchi-Grey relational and ANOVA to investigate effects of parameters [8].

Mandal et all conducted experimental work based on L9 orthogonal array with three parameters. These were depth of cut feed rate, cutting speed at three levels. They investigated machinability of AISI 4340 steel and found that depth of cut had maximum contribution on tool wear [9].

Vishnu et all made a study to investigate effects of type of machining conditions, cutting speed, feed rate, depth of cut, type of tool on surface roughness of EN-353 Alloy Steel in turning operation. They used L27 orthogonal array in experiments and ANOVA to dedicate influence of parameters. As a result they found that type of coolant had been the most effective factor [10].

In this study, experiments were planned according to Taguchi method, surface roughness was evaluated statistically using ANOVA in the milling of AISI 1040 stainless steel.

## 2. MATERIALS AND METHODS

### 2.1. Taguchi method

Taguchi method is an experiment design and optimization method based on parameter design, system design and tolerance design. Most commonly used in statistical analysis of data collected within the scope of quality assurance systems. Taguchi's experimental design method is a very useful method to detect the optimum combination between different levels of different parameters. This technique had been popular in the world after the 1980s. The benefit of Taguchi design is that many factors can be considered together. It also searches for nominal design points that are insensitive to changes in production and user environments to improve productivity in production and reliability in the performance of a product. At the same time noise factors can be checked. Although similar to the experimental design (DOE/design of experiment), the Taguchi design performs only combinations of balanced (orthogonal) experiments, making Taguchi design more effective than fractional factorial design. Industries can greatly reduce product development cycle time for both design and production, thereby reducing costs and increasing profits using the Taguchi method. Besides, Taguchi allows examine to the variability caused by noise factors, which are usually neglected in the traditional DOE approach [11].

In cases where a considerable amount of experimental work is required for all combinations involving each level of each parameter, it is possible to achieve a much lower number of experimental studies using the Taguchi method. The methodology developed in the Taguchi experimental design method consists of three basic concepts; system design, parameter design and tolerance design [12, 13].

### 2.2. Work piece material

The work piece material selected for investigation is AISI 1040 steel with the compositions as shown in table 1. The AISI 1040 steel used in the test is of the general production grade class and is widely used in the market. Since it is suitable for heat treatment, it is used in many mold sets, apparatus making, automotive sector, parts subjected to various difficulties, transferring miller and some gears. It has a tensile strength of 600 MPa, a modulus of elasticity of 210 GPa and a 24% elongation. The dimensions of the work piece used in tests are 20X150X80 $mm^3$.

Table 1. Chemical content of the workpiece material

| C % | Si % | Mn % | $P_{max}$ % | $S_{max}$ % |
|---|---|---|---|---|
| 0,40-0,50 | 0,25-0,35 | 0,60-0,90 | 0,04 | 0,05 |

## 2.3. Experimental plan and procedure

Three different parameters were chosen in the experiment design: Feed per tooth (Fpt), spindle speed (rpm), cooling type (Ct). Selected parameters and levels are specified in Table 2. The most suitable orthogonal array $L_{16}$ ($4^2x2^1$) was selected to determine optimum conditions and analyse the parameters [14]. The $L_{16}$ mixed level orthogonal array shown in table 3.

Table 2. Control parameters and their levels

| Symbol | Parameters | Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|---|---|
| A | Fpt mm/tooth | 0.08 | 0.12 | 0.16 | 0.20 |
| B | rpm | 2000 | 3000 | 4000 | 5000 |
| C | Ct | Air | Liquid | - | - |

All statistical analyses were performed using the Minitab 17 statistical package program at 90% confidence level.

Experimental samples were prepared at TAKSAN brand TMC 700V model CNC vertical machining center in Sakarya University Mechanical Engineering Department Laboratory.

Table 3. The $L_{16}$ mixed level ($4^2x2^1$) orthogonal array

| Experiment # | Factor A | Factor B | Factor C |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 2 | 1 | 1 |
| 3 | 3 | 1 | 2 |
| 4 | 4 | 1 | 2 |
| 5 | 1 | 2 | 1 |
| 6 | 2 | *2* | 1 |
| 7 | 3 | *2* | 2 |
| 8 | 4 | 2 | 2 |
| 9 | 1 | 3 | 2 |
| 10 | 2 | 3 | 2 |
| 11 | 3 | 3 | 1 |
| 12 | 4 | 3 | 1 |
| 13 | 1 | 4 | 2 |
| 14 | 2 | 4 | 2 |
| 15 | 3 | 4 | 1 |
| 16 | 4 | 4 | 1 |

MAHR-MARSURF PS1 model desktop roughness measurement instrument was used to measure surface roughness values and is shown in figure 1. Measurements were taken at room temperature. The instrument measures according to DIN EN ISO 3274 standards. Measurements were taken from the workpiece on the same axis at one point. The cutting length (Lc) was chosen as 0.8 mm and the exemplification length (Lt) as 5.6 mm for the measurement of the surface roughness values which occurred during machining on the workpiece.

APXT1035PDSR-MM coated cementitious carbide endmill cutter manufactured by Korloy, was used for milling in the sample AISI 1040 stainless steel at 20x150x80 mm3. The diameter of the endmill was selected as 16 mm.

# 3. RESULTS AND DISCUSSION

## 3.1. S/N ratio results

The average surface roughness (µm) measurements made and their average values are given in Table 4.

Optimization was done with the help of the results obtained. In this optimization process, there are three different convenient functions known as the Taguchi loss function, also referred to as the signal to noise ratio (S/N) function. They are " smallest best, the highest (the largest) is the best, the nominal 'is the best' cases. The aim of this work was to decrease surface roughness. Therefore "the smallest the better" quality characteristic was used as shown in equation 1.

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

Here $y_i$ =the observed data at the $i_{th}$ experiment and n= the number of the experiments [4].

Figure 1. Desktop roughness measurement instrument

Table 4. The experimental results

| Experiment # | Feed per tooth (mm/tooth) | Spindle speed (rpm) | Cooling type | Surface Roughness, Ra (µm) | S/N ratio for Ra (dB) |
|---|---|---|---|---|---|
| 1 | 0.08 | 2000 | Air | 1.121 | -0.9902 |
| 2 | 0.12 | 2000 | Air | 1.279 | -2.1374 |
| 3 | 0.16 | 2000 | Liquid | 1.336 | -2.5161 |
| 4 | 0.20 | 2000 | Liquid | 1.392 | -2.8697 |
| 5 | 0.08 | 3000 | Air | 1.313 | -2.3653 |
| 6 | 0.12 | 3000 | Air | 1.501 | -3.5291 |
| 7 | 0.16 | 3000 | Liquid | 1.599 | -4.0770 |
| 8 | 0.20 | 3000 | Liquid | 1.497 | -3.5059 |
| 9 | 0.08 | 4000 | Liquid | 2.350 | -7.4232 |
| 10 | 0.12 | 4000 | Liquid | 3.586 | -11.0928 |
| 11 | 0.16 | 4000 | Air | 2.628 | -8.3917 |
| 12 | 0.20 | 4000 | Air | 3.687 | -11.3341 |
| 13 | 0.08 | 5000 | Liquid | 2.287 | -7.1853 |
| 14 | 0.12 | 5000 | Liquid | 1.919 | -5.6615 |
| 15 | 0.16 | 5000 | Air | 2.367 | -7.4830 |
| 16 | 0.20 | 5000 | Air | 2.882 | -9.1924 |

Taguchi analysis, " the smallest better " signal noise ratios (S/N) according to the surface roughness (µm) of the values indicating the order of the effect of the values shown in table 5. The optimal levels for optimum surface roughness can be seen from this table. The graphical forms of the levels of control factors for Ra given in Table 5 are illustrated in figure 2. The best level of each factor was found by looking at the highest S / N ratio in the levels of its control factor. Accordingly, factor A (Level 1, S/N=-4.491), factor B (Level 1, S/N=-2.128) and factor C (Level 2, S/N=-5.541) were the factors that gave the best $R_a$ value. That means an optimum Ra value can be acquired from these levels of factors.

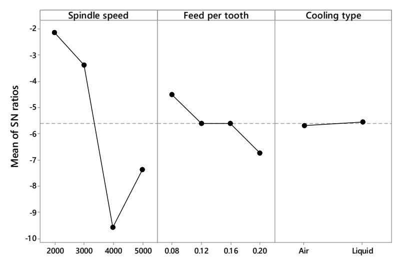


Figure 2. S/N graphs for surface roughness

Table 5. S/N response table for surface roughness

| Level | A | B | C |
|---|---|---|---|
| 1 | -4.491 | -2.128 | -5.678 |
| 2 | -5.605 | -3.369 | -5.541 |
| 3 | -5.617 | -9.560 | - |
| 4 | -6.725 | -7.381 | - |
| Delta | 2.234 | 7.432 | 0.136 |
| Rank | 2 | 1 | 3 |

### 3.2. ANOVA results

With Variance Analysis (ANOVA), the effects of which factors are effective on the process are determined statistically. In the analysis of variance, the aim is to determine the effects of the factors examined on how much they affect the output values selected to measure the quality and how the different levels cause the variability. In addition, the statistical reliability of the results obtained is also tested. Analysis was conducted with ANOVA to determine the effects of feed per tooth, spindle speed and cooling type on surface roughness. The ANOVA results of the surface roughness are given in table 6. The analysis was performed with a 10% significance level and a 90% confidence level.

Table 6. Results of ANOVA for surface roughness

| Variance source | Degree of freedom (DoF) | Sum of squares(SS) | Mean square (MS) | F ratio | Contribution rate (%) |
|---|---|---|---|---|---|
| A | 3 | 0.7338 | 0.24459 | 1.71 | 7 |
| B | 3 | 8.1682 | 2.72272 | 19.09 | 80 |
| C | 1 | 0.0411 | 0.04108 | 0.29 | 0.4 |
| Error | 8 | 1.1412 | 0.14265 | - | 13 |
| Total | 15 | 10.0842 | - | - | 100 |

The importance of control factors in ANOVA is defined by comparing the F values of each control factor. The percentage value of each parameter contribution and the degree of impact on the process performance is shown in the last column of the table. The contribution of A, B and C factors to surface roughness was found to be 7%, 80% and 0.4%, respectively (Table 6). So the most dominant factor affecting the surface roughness was feed per tooth (factor B, 80%).

### 3.3. Confirmation tests

The last step of Taguchi method is to control optimum levels. So, verification experiments of the control factors were performed with optimum levels. Confirmation test results are shown in table 7.

Table 7. Confirmation test results

| | Prediction | Experimental |
|---|---|---|
| Level | A1B1C2 | A1B1C2 |
| Parameters | 2000 0.08 Liquid | 2000 0.08 Liquid |
| Average surface roughness | 0.952 | 1.03 |

According to the difference between actual result and prediction calculated error is %7.5. This value is within acceptable level. That means, the optimization for surface roughness was obtained in confidence interval.

## 4. CONCLUSION

In this work, the effects on the average surface roughness of the feed per tooth, spindle speed, cooling type parameters in the milling of the AISI 1040 Stainless Steel were evaluated using the

Taguchi test design method. The following results may be drawn.

- The best average surface roughness value was at $A_1B_1C_2$ (i.e., feed per tooth=0.08 mm/tooth, spindle speed=2000 rpm, cooling type=liquid).
- It was observed that the spindle speed was the most significant factor in the roughness change with the ratio of 80 %, and this parameter was followed by feed per tooth (7%) and cooling type (0.4%) interactions according to the order of significance.
- Measured values were within the 90% confidence level according to the confirmation experiments.

These results show that the Taguchi method is a trusty process for reducing the machining time and production costs of milling AISI 1040 stainless steel. These results can be used for future academic research as well as industrial applications.

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