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Full Length Research Paper

Determination and optimization of the effect of cutting parameters and workpiece length on the geometric tolerances and surface roughness in turning operation

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In this work, the geometric tolerance and surface quality of an aluminium piece produced by turning is analysed. The effect of the length and diameter of working piece, cutting depth and feed were also investigated. The cutting speed, which is an important machining parameter, was kept constant in this study. Going from past works experience the effect of cutting speed was ignored. Statically method of Taguchi was used in this work in order to obtain more reliable and optimum results. By this method, time and cost savings were made, and the test results were optimized. The relation between the dependent and independent variables were also modelled by regression analysis. The results showed that cutting force, surface roughness, cylindricity and vibration were minimised in machining process and production quality was improved.

Key words: Taguchi method, turning, geometric tolerance, surface quality, regression analysis.

INTRODUCTION

The present study examined production variables in metal machining operations. The primary aim of this study was to determine the effect of cutting forces on workpiece cylindricity, surface roughness and vibration (Segonds et al, 2006; Benardos et al, 2006; Gao et al, 2007; Carrino et al, 2002) and to enable production of low-cost, high-quality products.

In turning, which is a widespread machining operation, variables involved in the machining process are the primary factors that directly affect the quality of a product (Segonds et al., 2006; Benardos et al., 2006; Gao et al., 2007; Carrino et al., 2002; Ozcatalbas and Bas, 2006; Ciftci, 2005). Although consulting manuals is helpful in identification of machining variables, theoretical and practical applications are not always consistent. This issue, which is quite common in sciences, has been analyzed by many studies. Several studies have examined the optimization of these issues (Isik and Cakir, 2002; Duran and Nalbant, 2005; Lin et al., 2001; Saglam et al., 2007).

In machine-turning, the use of a centering tool like a tail stock has an impact on the cylindricity value of the part. During machining, the workpiece is exposed to numerous forces generated by the cutting tool. Due to the effects of these forces on the geometrical structure of the part, the parts might not be produced with the desired cylindricity value (Segonds et al., 2006; Benardos et al., 2006; Carrino et al., 2002).

Due to its structure, aluminum is a material with low geometrical moment of inertia. Depending on machining conditions, buckling can occur in these materials. This buckling generates deflection forces that reduce cylindricity. In the experiment, the Taguchi method was used. Thus, unnecessary experiments were avoided and cost-reduction was achieved (Davim, 2003; Roy, 1990; Danacioglu and Muluk, 1999; Kurt et al., 2009). Experiments that used the Taguchi method measured forces applied on the workpiece, cutting forces and vibration between a maximum and minimum range. Regression analysis was used to model the relationship between

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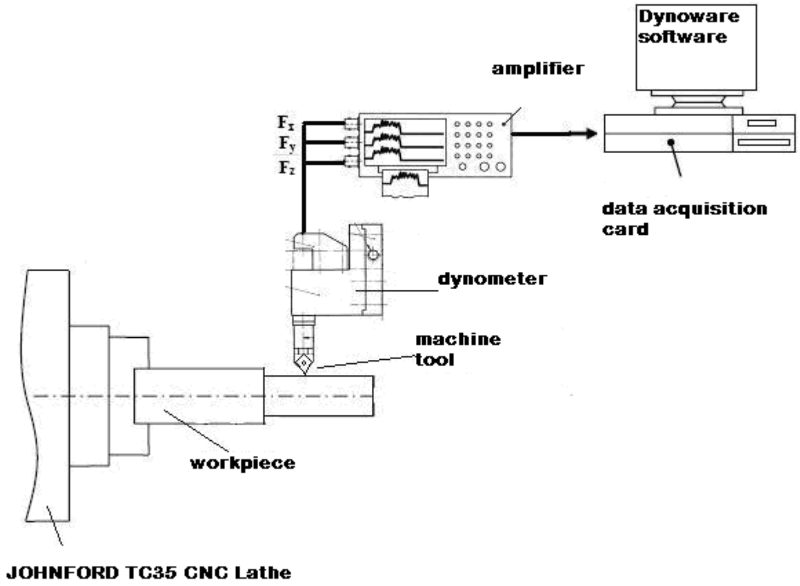

Figure 1. Experimental set-up.

Table 1. Experiment factors and their levels.

	Factor	Unit	1 Level	2 Level	3 Level
1	Length (A)	mm	50	70	90
2	Diameter (B)	mm	25	20	15
3	Cutting depth (C)	mm	0.5	1.0	1.5
4	Feed (D)	mm/rev	0.15	0.30	0.45

dependent-independent variables. Thus, estimated values could be obtained in future studies without the need for further experiments (Turhan, 2009).

MATERIALS AND METHODS

Al 2017 aluminum material was used in the present study. The experimental samples were rod shaped with 150 mm length and 25 mm diameter. The JOHNFORD TC 35 CNC Fanuc 0T CNC Lathe with 20 HP engine power was used in the experiments. DNMG 150608-2C KX20 inserts were used, supplied by safety group. Surface roughness of the workpiece after machining was measured with A MAHR-Perthometer. A KISTLER 9121 force sensor, KISTLER 5019b charge amplifier and DynoWare analysis program were used for force measurement in the experiments (Figure 1). Dimension and location sizes of the experiment materials were measured with Mitutoyo Crysta-Apex C574 device and the vibrations that occurred during cutting were measured with Brüel and Schenk brand Vibrotest 60 device.

Experimental design

One of the most important aims of this study was to contribute to industrial applications and to produce real solutions. With this aim, the preferred factors were process parameters, machining conditions and cutting tools currently used in manufacturing industry. In this context, aluminum material was selected due to its wide range of industrial applications, light weight, high-resistance and easy-to shape properties. Among the parameters that can be used in machining of aluminum, feed, cutting depth, workpiece length and diameter were taken into account. We aimed to choose the most appropriate factors, optimal cutting forces, surface roughness, minimal vibration and optimal dimensional precision in workpiece. Table 1 shows the chosen factors and their levels.

In this study, cutting speed was kept constant at n = 2500 rev/min. Considering the factors in Table 2 as the optimum design for the experimental study, a 9 experiment Taguchi L_9 orthogonal index was selected. Table 2 shows L_9 experimental design determined with Minitab 15 statistical software.

RESULTS

Cutting force, vibration, surface roughness and cylindricity measurement

During the experimental study, cutting forces and vibrations occurring during cutting were measured for each machining condition. In addition, surface roughness and cylindricity values of each specimen were measured. The Ra and cylindricity values obtained after the measurement of cutting forces and vibration are indicated

Table 2. Taguchi L_9 experiment design.

Experiment no	Variables	(A) Length (mm)	(B) Diameter (mm)	(C) Cutting depth (mm)	(D) Feed (mm/rev)
1	$A_1B_1C_1 D_1$	1	1	1	1
2	$A_1B_2C_2 D_2$	1	2	2	2
3	$A_1B_3C_3 D_3$	1	3	3	3
4	$A_2B_1C_2 D_3$	2	1	2	3
5	$A_2B_2C_3 D_1$	2	2	3	1
6	$A_2B_3C_1 D_2$	2	3	1	2
7	$A_3B_1C_3 D_2$	3	1	3	2
8	$A_3B_2C_1 D_3$	3	2	1	3
9	$A_3B_3C_2 D_1$	3	3	2	1

Table 3. Cutting force (F), vibration, Ra and cylindricity error values.

Experiment no.	Variables	F (N)	Ra (µm)	Cylindricity error (mm)	Vibration-acceleration (m/s^2)
1	$A_1B_1C_1 D_1$	94	0.831	0.019	0.168
2	$A_1B_2C_2 D_2$	482	7.824	0.071	4.940
3	$A_1B_3C_3 D_3$	999	6.228	0.072	0.173
4	$A_2B_1C_2 D_3$	666	7.135	0.359	0.131
5	$A_2B_2C_3 D_1$	483	1.660	0.049	5.696
6	$A_2B_3C_1 D_2$	269	3.560	0.068	1.559
7	$A_3B_1C_3 D_2$	841	3.394	0.55	0.104
8	$A_3B_2C_1 D_3$	565	9.970	0.105	1.760
9	$A_3B_3C_2 D_1$	791	2.708	0.124	2.838

Table 4. Cutting force (F) values.

Experiment no.	Variables	F (N)	S/N ratio (dB)
1	$A_1B_1C_1 D_1$	94	-39.4626
2	$A_1B_2C_2 D_2$	482	-53.6609
3	$A_1B_3C_3 D_3$	999	-59.9913
4	$A_2B_1C_2 D_3$	666	-56.4695
5	$A_2B_2C_3 D_1$	483	-53.6789
6	$A_2B_3C_1 D_2$	269	-48,5950
7	$A_3B_1C_3 D_2$	841	-58.4959
8	$A_3B_2C_1 D_3$	565	-55.0410
9	$A_3B_3C_2 D_1$	791	-57.9635

in Table 3.

Analysis and optimization of measurement results

Cutting force

In this turning process, maximum cutting force was 999 N and the minimum cutting force was 94 N (Table 4). This result indicates the benefit of optimization in the turning process.

Surface roughness (Ra)

Surface roughness values and S/N ratios obtained after the turning of the aluminum material are given in Table 5. The minimum surface roughness value was 0.831 µm.

Table 5. S/N ratios of Ra values.

Experiment no.	Variables	Ra (µm)	S/N ratio (dB)
1	$A_1B_1C_1 D_1$	0.831	1.9599
2	$A_1B_2C_2 D_2$	7.824	-16.4224
3	$A_1B_3C_3 D_3$	6.228	-15.7393
4	$A_2B_1C_2 D_3$	7.135	-17.0849
5	$A_2B_2C_3 D_1$	1.660	-4.3602
6	$A_2B_3C_1 D_2$	3.560	-10.5655
7	$A_3B_1C_3 D_2$	3.394	-10.2216
8	$A_3B_2C_1 D_3$	9.970	-20.4979
9	$A_3B_3C_2 D_1$	2.708	-10.3413

Work piece cylindricity error

Workpiece cylindricity error and S/N ratios of after each experiment are given in Table 6.

Vibration

Table 7 indicates vibration during cutting and S/N ratios for these vibrations.

Determination of estimated values

Estimation of minimum F value

Table 8 shows optimal levels for the factors, based on the S/N ratios obtained from experiments. Based on the values shown in Table 12, optimal F values were estimated as follows:

Estimated min. F values;

$$\text{Min. F} = A_1 + B_1 + C_1 + D_1 - 3\,(Y) \quad (1)$$
$$= 525 + 533.667 + 309.333 + 456 - 3\,(576.41)$$
$$= 94.8\ \text{N}$$

Estimation of minimum Ra value

Table 9 shows optimal levels for the factors, based on the S/N ratios obtained from experiments. Based on the values shown in Table 13, optimal Ra values were estimated as follows:

Estimated min. Ra values**;**

$$\text{Min. Ra} = A_1 + B_1 + C_1 + D_1 - 3\,(Y) \quad (2)$$
$$= 4.5150 + 3.7303 + 4.9210 + 1.9130 - 3\,(4.7580)$$
$$= 0.805\ \mu\text{m}$$

Estimation of minimum cylindricity error values

Table 10 shows optimal levels for the factors, based on the S/N ratios obtained from experiments.

Estimated minimum cylindricity error values:

$$\text{Min. Error} = A_1 + B_2 + C_1 + D_1 - 3\,(Y) \quad (3)$$
$$= 0.0540 + 0.0750 + 0.0640 + 0.0640 - 3(0.0786)$$
$$= 0.021\ \text{mm}$$

Estimation of minimum vibration values

Table 11 shows optimal levels for the factors, based on the S/N ratios obtained from experiments.

$$\text{Min. Vibration Ratio} = A_1 + B_1 + C_3 + D_3 - 3\,(Y) \quad (4)$$
$$= 0.89367 + 1.09503 + 1.03037 + 1.022 - 3(1.17945)$$
$$= 0.502$$

Confirmation experiments

An analysis of the cutting force results indicates that the results were quite satisfactory. It was concluded that Taguchi optimization can be successfully applied in experiments in the present context (Tables 12 to 15).

Regression analysis

In this context, based on the interaction between the factors that affect surface roughness during cutting, a linear regression model of these factors is given below.

Regression analysis for F cutting force

$$F = -536 + 104A + 76.3\,B + 233C + 144\,D + (\varepsilon)\ R^2 = 0.846 \quad (5)$$

R_a Regression analysis for surface roughness

$$Ra = -1.76 + 0.596\,A + 0.266\,B - 0.624\,C + 3.02\,D + (\varepsilon)\ R^2 = 0.777 \quad (6)$$

Regression analysis for cylindricity error;

$$\text{Error} = -0.101 + 0.103A - 0.111\,B + 0.0798C + 0.0573\,D + (\varepsilon)\ R^2 = 0.772 \quad (7)$$

Table 6. S/N ratios for **cylindricity** error.

Experiment no.	Variables	Error (mm)	S/N ratio (dB)
1	$A_1B_1C_1\ D_1$	0.019	34.4249
2	$A_1B_2C_2\ D_2$	0.071	22.9748
3	$A_1B_3C_3\ D_3$	0.072	22.8534
4	$A_2B_1C_2\ D_3$	0.359	8.8981
5	$A_2B_2C_3\ D_1$	0.049	26.1961
6	$A_2B_3C_1\ D_2$	0.068	23.3498
7	$A_3B_1C_3\ D_2$	0.55	5.1927
8	$A_3B_2C_1\ D_3$	0.105	19.5762
9	$A_3B_3C_2\ D_1$	0.124	18.1316

Table 7. Vibration during cutting and associated S/N ratios.

Experiment No.	Variables	Vibration-acceleration (m/s^2)	S/N ratio (dB)
1	$A_1B_1C_1\ D_1$	0.6680	15.4938
2	$A_1B_2C_2\ D_2$	0.7400	-13.8745
3	$A_1B_3C_3\ D_3$	1.2730	15.2391
4	$A_2B_1C_2\ D_3$	0.8131	17.6546
5	$A_2B_2C_3\ D_1$	0.8600	-15.1114
6	$A_2B_3C_1\ D_2$	1.1590	-3.8569
7	$A_3B_1C_3\ D_2$	1.8040	19.6593
8	$A_3B_2C_1\ D_3$	1.7600	-4.9103
9	$A_3B_3C_2\ D_1$	1.5380	-9.0602

Table 8. Optimal results for $F_{max.}$

Factors	Level	F respond value
A	1	525
B	1	533.667
C	1	309.333
D	1	456

Table 9. Optimal results for Ra.

Factors	Level	Ra respond value
A	1	4.51500
B	1	3.73033
C	1	4.92100
D	1	1.91300

Table 10. Minimal results for cylindricity error.

Factors	Level	Error respond value
A	1	0.0540
B	2	0.0750
C	1	0.0640
D	1	0.0640

Table 11. Minimal results for vibration.

Factors	Level	Vibration respond value
A	1	0.89367
B	1	1.09503
C	2	1.03037
D	1	1.02200

Table 12. Optimal results for F.

	Estimated	Confirmation experiment
Level	$A_1\ B_1\ C_1\ D_1$	$A_1\ B_1\ C_1\ D_1$
Cutting force values (N)	94,8	94

Table 13. Optimal results for Ra.

	Estimated	Confirmation experiment
Level	$A_1\ B_1\ C_1\ D_1$	$A_1\ B_1\ C_1\ D_1$
Roughness value (µm)	0.805	0.831

Table 14. Optimal results for cylindricity error.

	Estimated	Confirmation experiment
Level	$A_1 B_2 C_1 D_1$	$A_1 B_2 C_1 D_1$
Cylindricity error values (mm)	0.021	0.019

Table 15. Optimal results for vibration.

	Estimated	Confirmation experiment
Level	$A_1 B_1 C_2 D_1$	$A_1 B_1 C_2 D_1$
Vibration-acceleration values (m/s^2)	0.502	0,6680

Table 16. S/N Ratios of F values.

Level	A	B	C	D
1	-51.0383	-51.4760	-47.6995	-50.3683
2	-52.9145	-54.1270	-56.0313	-53.5840
3	-57.1668	-55.5166	-57.3887	-57.1673
Δ $_{\text{max-min}}$	6.1285	4.0406	9.6892	6.7989
Rank	3	4	1	2

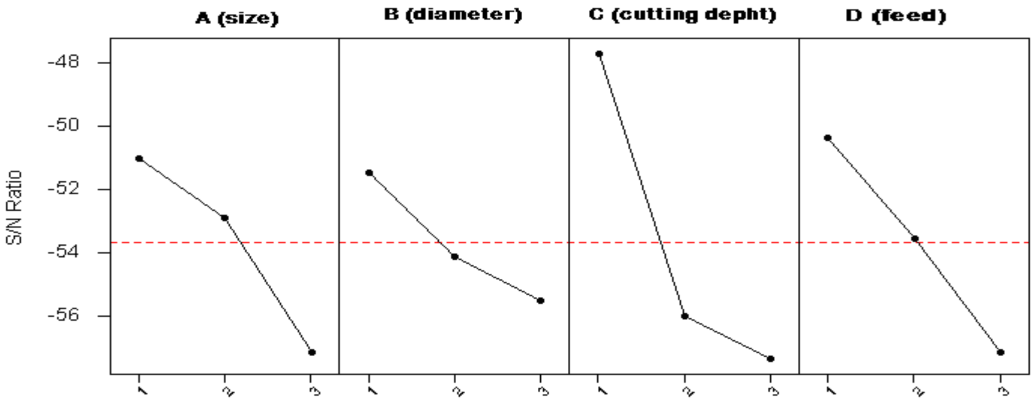

Figure 2. Signal-to-noise ratio.

Regression analysis for vibration;

$$\text{Vibration} = -0.233 + 0.403\,A + 0.114\,B + 0.058\,C + 0.130\,D + (\varepsilon)n \quad R^{2m} = 0.756 \qquad (8)$$

DISCUSSION

Evaluation of cutting force

As machining process involves shaping materials by machining method, cutting forces are inevitable parts of this process. The optimization of cutting forces during machining is important, as this can improve many aspects of the process. The present study used Taguchi's principle of "the smallest is the best" to define the quality characteristics for the optimization of cutting forces. Table 4 indicates S/N ratios (S/N = signal-to-noise) of the cutting forces that occur in machining of aluminum material.

In Taguchi experiment design, S/N ratios are used in evaluation of quality characteristics. The measurement is based on the experiment, is based on the identification of the ratio of signal-to-noise (Table 16), where noise is undesirable. Figure 2 shows the graph of signal-to-noise ratios expressing the effect of workpiece length, diameter, cutting depth and feed rate on maximum cutting force. In addition to the optimization, the two most effective parameters in generation of cutting forces are given in Figure 3. It was found that, in addition to

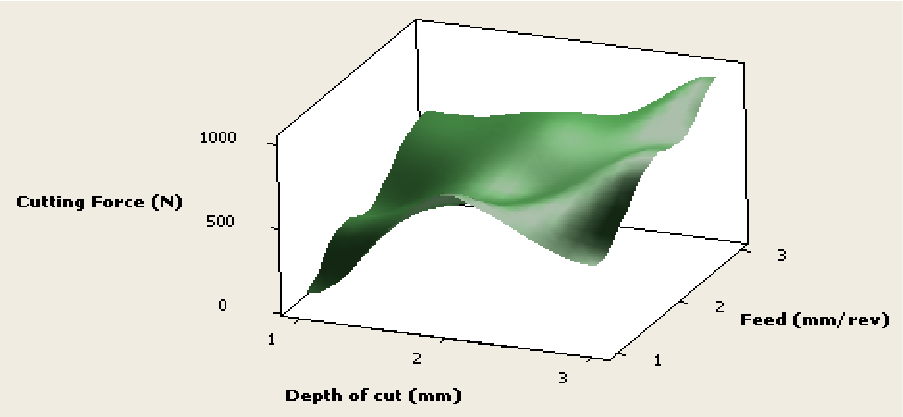

Figure 3. The effect of cutting depth and feed rate on cutting force.

Table 17. S/N ratios of Ra values.

Level	A	B	C	D
1	-10.0672	-8.4489	-9.7012	-4.2472
2	-10.6702	-13.7602	-14.6162	-12.4032
3	-13.6869	-12.2153	-10.1070	-17.7740
Δ max-min	3.6197	5.3113	4.9150	13.5269
Rank	4	2	3	1

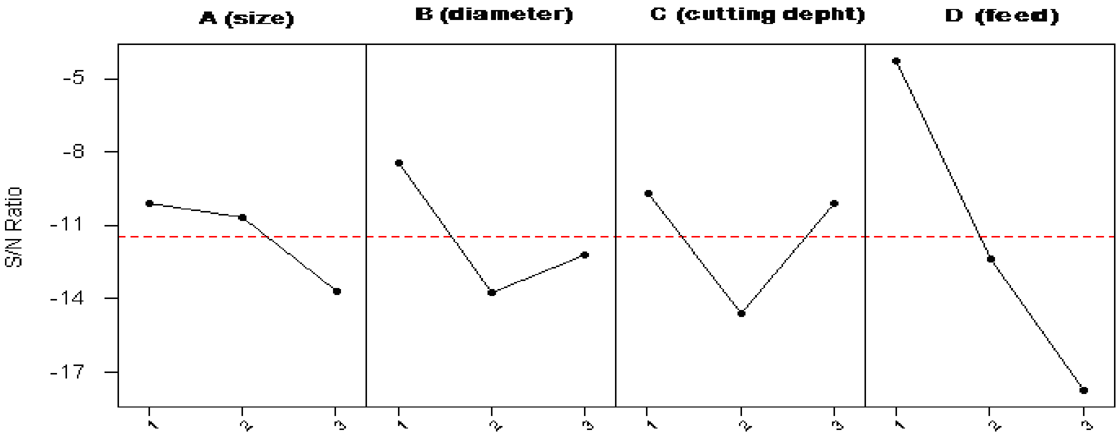

Figure 4. Signal-to-noise ratios.

machining parameters, workpiece dimensions also had a role in the formation of cutting forces, which are another important field of analysis in metal cutting.

Evaluation of surface roughness (Ra)

The most important factor in determining the surface quality of a machined surface is the surface roughness. Table 5 indicates S/N values for each level of the factors. Table 17 gives rank and delta values according to S/N values. Figure 4 shows a graph of signal-to-noise ratio. In machining processes, the workpiece material is an important factor. The effects of machining parameters on surface roughness are generally well known, and have been established, over time, by many studies. Figure 5 shows the effects on surface roughness of feed rate and workpiece diameter, two parameters that affect the

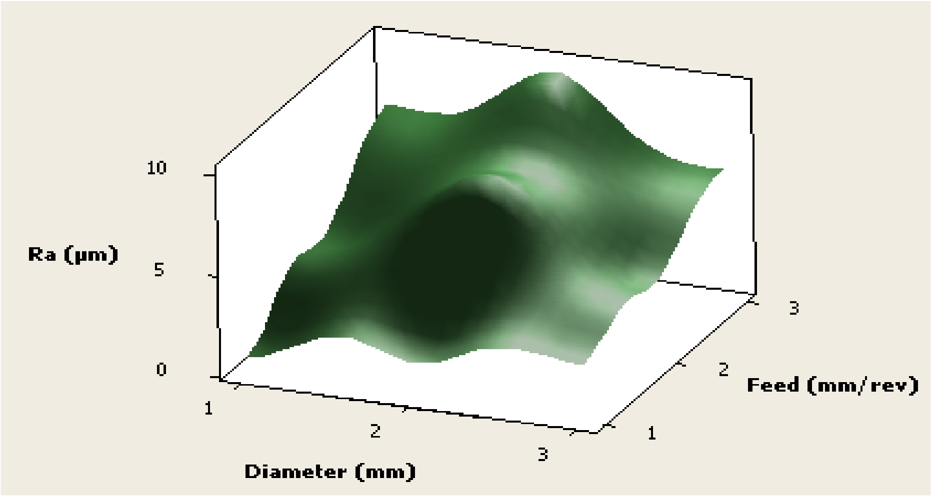

Figure 5. The effect of feed rate and workpiece diameter of surface roughness.

Table 18. S/N ratios for cylindricity error.

Level	A	B	C	D
1	26.7510	16.1719	25.7837	26.2509
2	19.4813	22.9157	16.6682	17.1725
3	14.3002	21.4449	18.0807	17.1092
$\Delta_{\text{max-min}}$	12.4509	6.7438	9.1155	9.1416
Rank	1	4	3	2

surface roughness values of workpieces. It was concluded that, for surface roughness, which is widely discussed and investigated in the literature, in addition to machining parameters, the dimension of the workpiece is also an important factor.

Evaluation of workpiece cylindricity error

Optimizing only the surface roughness of the machined workpiece does not mean that the workpiece meets the specified quality criteria. Factors such as machine tools, connection elements, cutting tool holders and oscillation of the workpiece can distort the dimensional precision of the workpiece beyond specified tolerances. Therefore, the study also examined the cylindricity of the workpiece. Table 18 indicates S/N values, delta and rank ratios for each machining parameter. Figure 6 shows a graph of noise ratios. Furthermore, Figure 7 indicates the effect of workpiece size and feed rate on error. These two parameters affect cylindricity precision in the workpiece. It was observed that the changes in aluminum material, connection sizes and the diameters of the workpiece have an effect on surface roughness and cylindricity, which are important for dimensional precision.

Evaluation of vibration

Since with the available technology it is not possible to keep the machine tool, cutting tool holder and other connection apparatus rigid, vibration during the chip formation is still analyzed. In this study, vibration during chip formation was measured and optimal cutting conditions were determined for minimal vibration. Vibration related S/N ratios for each parameter, which are considered as independent variables in chip formation, are given in Table 19. Figure 8 shows a graph of S/N ratios of these parameters. Among the effective parameters in formation of other measurable sizes two were identified and shown in a graph. In addition, in metal cutting process, vibration formation, two parameters affecting vibration formation and their levels of effect are given in Figure 9.

Evaluation of confirmation experiments

Optimal results were obtained experimentally, using Taguchi optimization. These results can sometimes involve any one of the existing experiments, however sometimes a separate experiment is required to produce optimal results. The results obtained from the confirmation

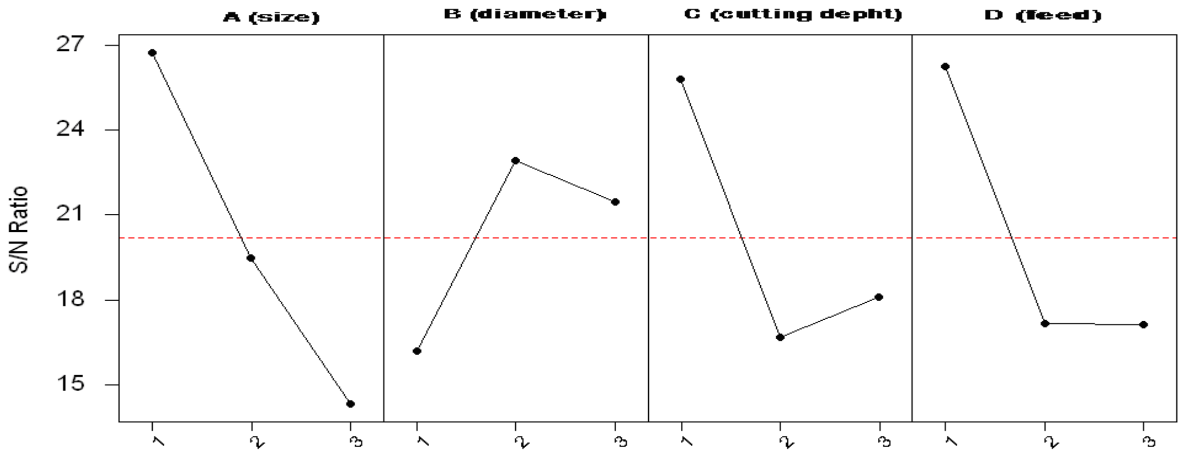

Figure 6. Signal-to-noise ratios.

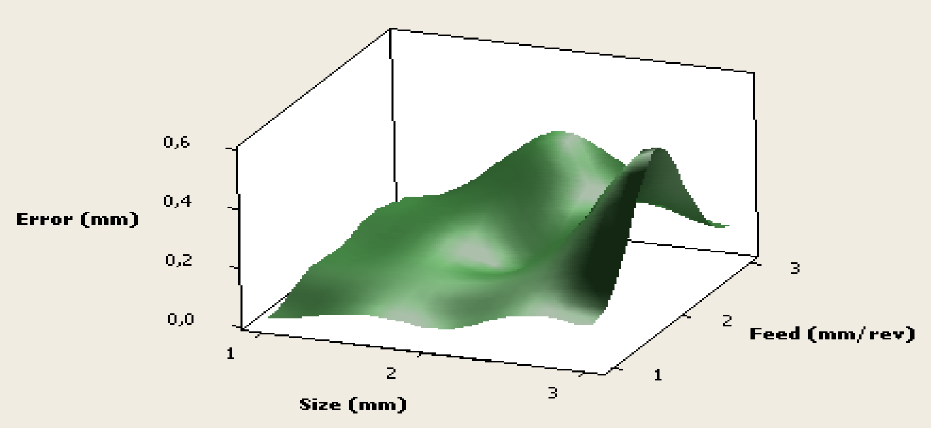

Figure 7. The effect of workpiece size and feed rate on workpiece cylindricity.

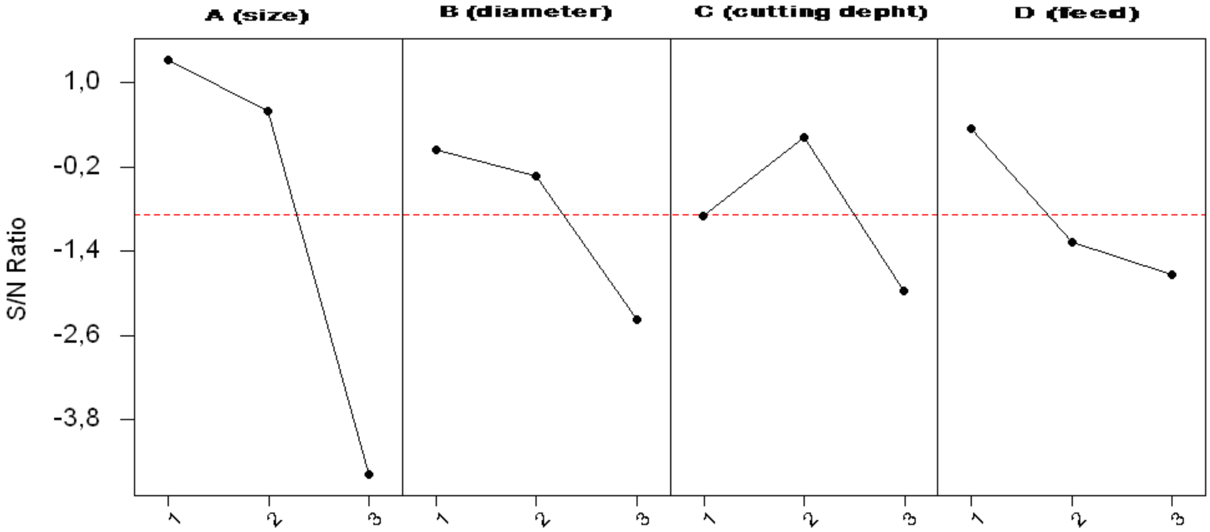

Figure 8. Signal noise ratios.

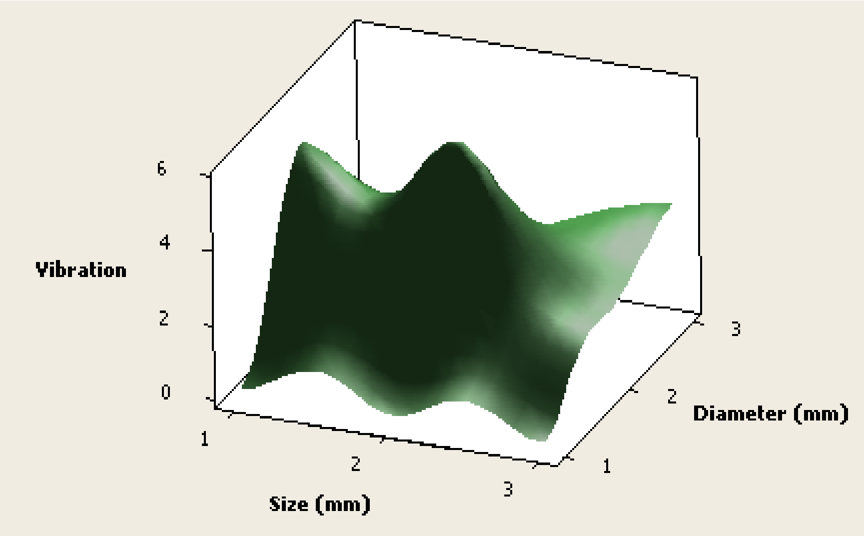

Figure 9. The effect of feed rate and workpiece diameter on vibration formation.

experiment reflect the success of the optimization. In this context, Tables 12 to 15 indicated cutting forces, surface roughness, cylindricity error and vibration values obtained from the confirmation experiments, in which optimal conditions are estimated following the calculations.

Evaluation of regression analysis

Regression models aim to determine the relationship between variables where a cause and effect relationship is estimated. In this context, in application of the regression model, estimating that there is a conceptual relationship between independent factors and dependent factors is highly important for the model developer. Considering these principles in a regression model, it would be correct to consider surface roughness and cutting force as the two most important variables contributing to achievement of optimal conditions in chip formation. The independent variables used in this model were (A) workpiece size, (B) diameter, (C) cutting depth and (D) feed.

Linear regression coefficients were obtained using Equations 5 to 8, where E indicates error. R2 is the coefficient expressing the appropriateness of the equation. Although an acceptable value of R2 can vary depending on the relationships between dependent and independent variables used in each discipline or model, the optimal value is the one that is closest to 1. As R2 gets closer to 1, it is considered that statistical approximation of the regression model to the real relationship increases. A regression model represents the relationship between the dependent and independent variables. According to Pearson coefficient, if R2 has a value of 0.80 and greater, it is considered a strong relationship, while 50 to 70% is considered to be a moderate relationship. In this case, when the modeled statistical regressions (Equations 5 to 8) are analyzed, it is understood that they are within acceptable limits. There is a particularly strong relationship between the variables in Equation 5. Based on this finding, it is concluded that the factors (independent factors) selected in the experimental study as having a strong effect on dependent variables (surface roughness, cutting force, cylindricity error and vibration) were accurately estimated. In this case, it is concluded that the regression model provides a good estimation of reality.

Conclusions

In this study, aluminum workpieces were produced by machine-turning, which is an important form of metal fabrication. The dimensional precision and surface quality of the workpiece were analyzed and the potential effects of variables such as workpiece size, workpiece diameter, cutting depth and feed rate on these dependent variables were investigated. In addition, cutting speed, which is an important machining parameter, was kept constant in this study. As a result of previous experiences and a review of the literature, it was decided that the effect of these parameters on the determined dependent variables could be ignored.

A Taguchi method was used in the study, in order to help obtain more reliable results and therefore save time and cost in a real production environment, by obtaining optimal results. This method informed the experimental design; fewer experiments were required and more efficient outcomes were achieved; thus, time and cost were reduced by avoiding unnecessary experiments. In addition, the experimental data were optimized and optimization was achieved. Furthermore, the relationship between the independent and dependent variables was modeled using regression analysis. It was therefore possible to produce estimated values for future works without the need for experimental studies. The results obtained with this study were as follows:

(i) Experimental and statistical methods were used. The parameters determined at the experimental design stage and the parameters necessary for improving dimensional precision of the workpiece were consistent. Thus, the study was successfully completed. In short, independent variables estimated for the dependent variables solved the problem.
(ii) The minimum surface roughness value was 0.831 µm.
(iii) The minimum cutting force was 94 N.
(iv) The minimum workpiece cylindricity error was 0.019 mm.
(v) The study also investigated vibration, which is considered to be important in generation of surface roughness and dimensional errors in metal cutting. The study determined appropriate cutting parameters to minimize vibration.
(vi) The Taguchi optimization method was successfully applied in the study. Machining parameters such as cutting forces, surface roughness, cylindricity and vibration were minimized; process performance was enhanced and product quality was improved.

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