GU J Sci, Part A, 6(1): 25-32 (2019)

Gazi University
Journal of Science
PART A: ENGINEERING AND INNOVATION
http://dergipark.gov.tr/gujsa

Optimization of Surface Roughness in Turning of AZ31 Magnesium Alloys with Taguchi Method

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Article Info

Received: 20/03/2019
Accepted: 28/03/2019

Keywords

Turning,
AZ31,
Taguchi method,
ANOVA,
Surface roughness

Abstract

In this paper, the effects of the different cutting parameters on the surface roughness in turning AZ31 magnesium alloys were investigated. Three cutting parameters, such as depth of cut (t), feed rate (f) and cutting speed (V), were used in the turning operation. Experiments were designed for L9 Taguchi's model. Tests were performed on a CNC lathe. The surface roughness values were measured in the tests. Taguchi and ANOVA analysis were evaluated to detect main effect parameters and their contribution ratios. The optimum cutting parameters for the surface roughness were computed as "t" at level 2 (2 mm), "f" at level 1 (0.2 mm/rev) and "V" at level 1 (320 m/min). Moreover, empirical equations were developed by using regression analysis (RA) to predict the surface roughness and compared to experimental results.

1. INTRODUCTION

Magnesium alloys have been widely used in automobile, electronics, and aerospace fields. Magnesium alloys are a promising material for attractive features that will replace aluminum and steel in structural and mechanical applications. They have a superior hardness-to-weight ratio, a high damping capacity, the lowest density among engineered metallic materials and the ease of recyclability [1]. At present, magnesium alloys are used for many applications due to their light weight instead of aluminum alloys [2,3]. Although near net shape manufacture of magnesium alloy parts is possible through various die casting techniques, more often than not machining steps will still need to be carried out on such parts. Researchers applied some optimization techniques to improve machining quality of the magnesium alloys in the literature. Sahu and Pal [3] investigated of the optimization of process parameters in friction stir welded AM20 magnesium alloy by Taguchi grey relational analysis. Tönshoff and Winkler investigated influence of tool coatings on the machining of magnesium. They found that TiN and PCD coated tools reduce cutting force, and result in improved surface quality even at high cutting speeds [4]. Shi et al., performed surface roughness and micro hardness in dry milling of magnesium alloy using Taguchi with grey relational analysis [5]. The optimum parameters for better surface quality in turning Mg-Ca3.0 alloy were investigated by Denkena and Lucas [6]. Umbrello [7] investigated of surface integrity in dry machining of Inconel 718. Jin and Liu [8] performed Effect of cutting speed on surface integrity and chip morphology in high-speed machining of PM nickel-based super alloy FGH95. Pu et al. have investigated the influence of tools with varying cutting edge radii on magnesium surfaces under dry and cryogenic machining conditions [9].

In this study, the effects of the various cutting parameters that are the depth of cut (t), the feed rate (f) and the cutting speed (V) on the surface roughness of the AZ31 magnesium alloy materials in turning process were identified by using Taguchi method. The highest contribution ratios of each parameter of the surface

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*Corresponding author, e-mail: omerasal@gazi.edu.tr roughness were performed by ANOVA analysis. Moreover, empirical equations was evaluated with regression analysis (RA) for the surface roughness and compared with experimental results.

2. MATERIAL AND METHOD

Experimental tests were performed in a CNC lathe under dry machining conditions. The work pieces of the experimental tests were used high-pressure die-cast AZ31 magnesium alloy bar with 92 mm diameter and 300 mm length. The test part was manufactured as Fig. 1 to do the experiments and controls easily.

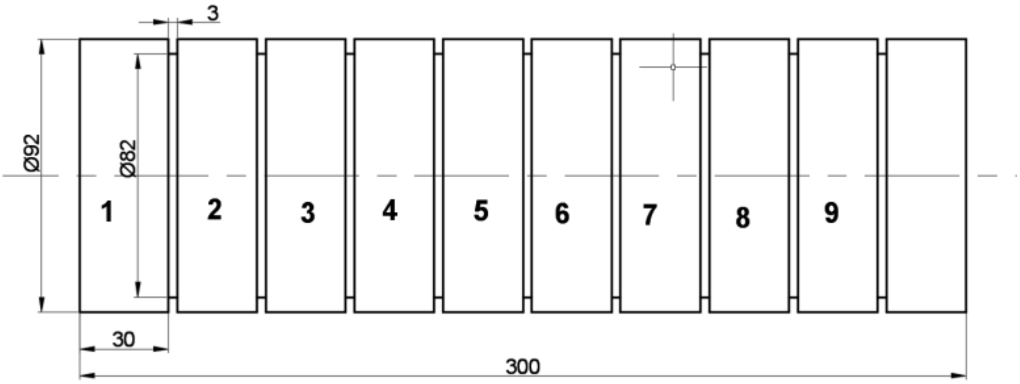

***Figure 1**. Test part*

The chemical composition of the AZ31 material was presented in Table 1

***Table 1**. The chemical composition (%) of AZ31 magnesium alloy.*

Al	Zn	Mn	Fe	Si	Cu	Ni	Mg
3.23	0.84	0.21	0.0032	0.014	0.0014	0.00042	Balance

The cutting tools coated PVD (SNMG120412-NM4 WSM10) were used in the machining process. Mahr Perthometer M1 type, given specifications (Table 2), was used as surface roughness measurement instrument. The surface roughness of the AZ31 alloy was measured with the measurement instrument.

***Table 2.** Specifications of the surface roughness measurement instrument*

Tracing speed	0.5 m/sn
Tracing force	0.75 mN
Stylus radius	2 µm
Sampling range	100 – 150 µm
Profile	12 mm
Filter	Gaussian
Sampling	0.25 – 0.8 – 2.5 (mm)
Measurement	1.75 – 5.6 – 17.5 (mm)
Roughness	Ra, Rz, Rmax

Three different cutting parameters, such as depth of cut, feed rate, and cutting speed (Table 3), were used for machining AZ31 alloy.

***Table 3.** The cutting parameters used in the machining AZ31 Magnesium Alloy*

Symbol	Machining Parameter	Coded levels		
		1	2	3
A	Depth of cut, t (mm)	1	2	3
B	Feed rate, f (mm/rev)	0.1	0.2	0.3
C	Cutting Speed, Vc (m/min)	320	512	820

3. RESULTS AND DISCUSSION

Normally, (3 x 3 x 3) 27 experiments are required for all machining parameters' levels (Table 3) in classical machining test. It is seen that the experiments mean time and cost. It is known that Taguchi method is preferred to conduct the experiments. Taguchi also is called design of experimental method that provide with minimum experiments to identify main effects of the using parameters in tests [10,11]. So in this paper, the effect of the cutting parameters on the surface roughness was investigated by using Taguchi method. Taguchi method was done to test AZ31 magnesium alloy in MINITAB. The control factors and each parameter used for experimental design were presented in Table 3. The numbers of experiments were reduced by the using of Taguchi method. The numbers of experiments were found enough as 9 by Taguchi in machining AZ31 magnesium alloy. In this way, the experimental works were designed as L9 (3*3) orthogonal array in Taguchi method. Taguchi L9 design of experiments model was given in Table 4.a.

Tests were fulfilled on a CNC Lathe according to Taguchi L9 model. The surface roughness (Ra) was measured for each of the test. Totally, 9 experiments were performed, two repeated. The tests results were given in Table 4.b.

It is known that the minimum surface roughness is very important criteria in machining methods, such as turning, milling, drilling. Moreover, there are a lot of factors that affect the surface roughness in machining methods, for example, federate, cutting edge radius, depth of cut, etc. Therefore, the results of the tests were analyzed to determine the main effects on surface roughness by using the analysis of Taguchi Design in MINITAB. The S/N ratio was used to analyze test results of the machining AZ31 magnesium alloy. The S/N ratio that is a method in the analysis of Taguchi Design was performed to evaluate the test results. There are several functions, such as, "*Lager is better*", "*Nominal is best*" and *"Smaller is better",* to analyze test results with Taguchi method.

In this experimental works, the main function that is the "*Smaller is better*" quality characteristics was preferred to determine the optimal cutting parameters for surface roughness. "*Smaller is better*" quality characteristics of the signal-to-noise (S/N) ratio was given as below:

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

***Table 4**. a) Experimental design for the L_9 orthogonal array, b) The tests results*

Exp. No	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

a)

Exp. No	A (t: mm)	B (f: mm/min)	C (V: m/min)	Ra (µm)
1	1	0.1	320	0.416
2	1	0.2	512	1.496
3	1	0.3	820	2.533
4	2	0.1	512	0.518
5	2	0.2	820	1.027
6	2	0.3	320	2.532
7	3	0.1	820	0.631
8	3	0.2	320	1.157
9	3	0.3	512	3.029

b)

Where η is the S/N ratio for the "*Smaller is better"* case, and y_i represents the surface roughness based on experimental results and *n* the number of repetitions in a trial [11-17]. Table 5 present the S/N ratio obtained from Eq. (1) for surface roughness. The effect of each factor at different levels can be determined by averaging the S/N ratios. To determine the "*Smaller is better"* surface roughness quality, the S/N ratio applied at each level of each factor (Table 5). The main effective factors and order shows in the Rank column. The numbers point order of the main factors out. The Rank numbers are obtained from the values of Delta column. If the Delta value is bigger than other the Rank value will be first number (1). So, the first main factor is B (feed rate) according to the number 1 of the Rank column. In other words, the parameter feed rate is the main factor for the surface roughness in turning AZ31 magnesium alloy.

Table 5. *Response table mean S/N ratio (η) for Ra (μ) (smaller is better)*

Symbol	Parameter	Mean S/N ratio, η				
		Level 1	Level 2	Level 3	Delta	Rank
A	Cutting depth, t (mm)	-1.3177	-0.8624	-2.2977	1.4353	3
B	Feed rate, f (mm/rev)	5.7770	-1.6656	-8.5893	14.3663	1
C	Cutting Speed, V (m/min)	-0.5726	-2.4704	-1.4349	1.8978	2

Also, the obtained results were presented in an S/N response graphical form as shown in Fig. 2. The trend of the curves in Fig. 2 shows the effects of the test factors. In other words, the shape of curves that are formed by the levels of factors tells us which factors are very or less important for test results. For example, the feed rate curve in Fig. 2 rises quickly. As a result, the feed rate is absolutely main factor for surface roughness of AZ31 magnesium alloy.

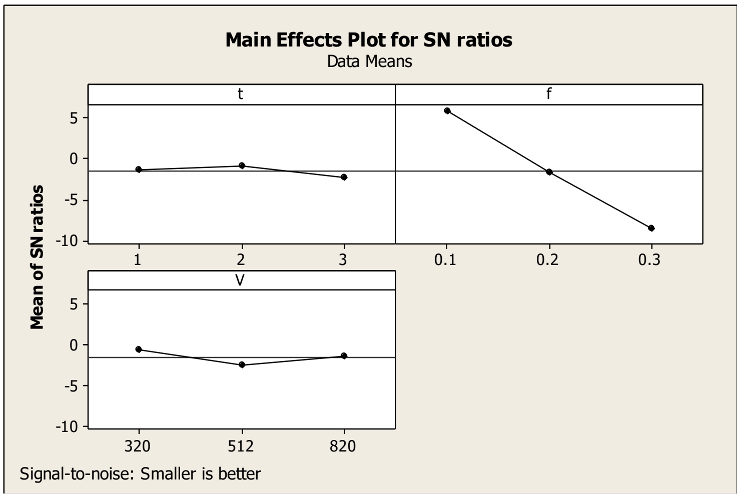

Figure 2. *Mean S/N ratio graph for surface roughness, Ra (μ)*

ANOVA was performed to investigate the effect the design parameters on quality characteristics [16]. The percent contribution ratio (PCR) was determined for surface roughness using ANOVA. The PCR to determine of influence of cutting parameters was computed from Eq. (2) [13-17]:

$$PCR = \left(\frac{SS_A - (V_e).(\upsilon_A)}{SS_T} \right) \times 100 \tag{2}$$

Where SS_A, is the sum of squares for parameter A. V_e is the variance of error, υ_A is the degrees of freedom of parameter A, and SS_T is the total sum of squares [18-19]. In addition, the effect of the cutting parameters on the surface roughness in turning process was evaluated by using ANOVA as regards PCR. As shown in Table 6, feed rates were found to be the major factor affecting the surface roughness (PCR:

94.18%) followed by cutting speed (PCR: 0.10 %). However, the depth of cut has no effect on surface roughness.

Table 6. *ANOVA results for surface roughness, Ra (µm) (for S/N ratios)*

Source	**Degrees of freedom (DoF)**	**Sequential sum of squares (SS)**	**Mean sum of squares (MS)**	**F-test**	**P-coefficient**	**PCR (%)**
Depth of cut	2	3.228	1.614	0.63	0.612	---
Feed rate	2	309.721	154.860	60.77	0.016	94.18
Cutting speed	2	5.417	2.709	1.06	0.485	0.10
Residual error	2	5.096	2.548			5.72
Total	8	323.462				100

In Table 7, the optimum cutting parameters were determined with *S/N* ratio by using the Taguchi method. The optimal cutting parameter for the best surface roughness with the criteria of the lowest response and lowest S/N ratio was obtained as A2B1C1 (Table 5). Also, the figure 1 appears the effects levels of the factors that make the surface roughness minimum. The depth of cut at level 2 (2 mm), feed rate at level 1 (0.1 mm/rev) and cutting speed at level 1 (320 m/min) provided the best results for optimum cutting parameters as regards surface roughness [20]. But, these parameters are not include L9 Taguchi model (Table 4). The A2B1C1 values that are t: 2 mm, f: 0.1 mm/rev. and v: 320 m/min., were not used in the experimental works. So, the levels were untested. For this reason, Taguchi method provides to predict the untested levels of factors. The predicted surface roughness for A2B1C1 was evaluated by Taguchi method. Moreover, a confirmation test was carried out for making certain of these parameters [18]. The having gotten results were presented in Table 7.

Table 7. *Results of confirmation tests for surface roughness, Ra (µm)*

	Optimal cutting parameters	
	Prediction	**Experimental**
Level	A2B1C1	A2B1C1
Surface roughness, Ra (µm)	7.32723	0.515
Mean S/N ratio	0.284778	5.7638

An equation can be computed for the predictive surface roughness. So, the regression analysis should be used by evaluating an equation. It is known that the regression analysis correlates among the used test parameters and find the coefficients for using in the equation [20]. In this paper, the regression analysis for the surface roughness equations obtained by using MINITAB software. The Coefficients for surface equations were given in Table 8.

Table 8. *Regression analysis results for surface roughness, Ra (µm)*

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	-0.7993	0.5073	-1.58	0.176
t	0.0620	0.1384	0.45	0.673
f	10.882	1.384	7.86	0.001
V	-0.0000343	0.0005488	-0.06	0.953

S = 0.339074 R-Sq = 92.5% R-Sq(adj) = 88.1%

The reliability for the Regression analysis was computed by 92.5%. Moreover, if the coefficients in table 8 are used, the equation will be obtained as follow.

$$Ra = -0.7993 + 0.0602\,t + 10.882\,f - 0.0000343\,V \tag{3}$$

In addition, Analysis of Variance for regression was evaluated in Table 9. In Table 9, the value of the P is 0.003 that shows accuracy of the ANOVA analysis. Also, the value shows the acceptability results of the analysis. Because, it is lower than 0.005 that is 95% confidence.

Table 9. *Regression analysis results for surface roughness, Ra (µm)*

Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	3	7.1282	2.3761	20.67	0.003
Residual Error	5	0.5749	0.1150		
Total	8	7.7030			

In addition, the four residual plots for Ra by Regression method were presented in Fig. 3. The plots can give an idea for the Regression analysis.

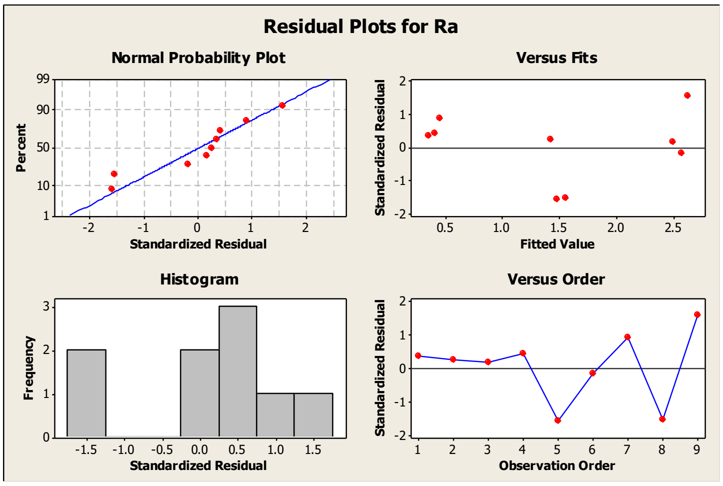

Figure 3. *The four residual plots for Ra by Regression method*

Finally, new results for Ra were found by using the regression equation (3). The obtained values are shown in Table 10. The percent error values evaluated from are shown a little bit high in Table 10. It is thought that the values are a reason of the L9 Taguchi model. The Taguchi L9 model limited for evaluating the regression analysis to predict the test results properly. If the large Taguchi model could be selected for example, L27, The regression predicted results would be more close the experiments results.

Table 10. *The tested results and the Regression equation results for surface roughness, Ra (µm)*

Ra (µm) Experimental	**Ra (µm) Regression Equation**	**Error (%)**
0.416	0.34212	17.7596
1.496	1.42559	4.7066
2.533	2.50512	1.1007
0.518	0.39759	23.2452
1.027	1.47712	43.8286
2.532	2.58412	2.0585
0.631	0.44912	28.8241
1.157	1.55612	34.4961
3.029	2.63959	12.8561

4. CONCLUSIONS

In this paper, the surface roughness of turning process for various cutting parameters, such as depth of cut, the feed rate and the cutting speed, were optimized by using Taguchi Method. The results can be listed as:

- The optimum cutting parameters for the lowest surface roughness were found as A2B1C1 with the depth of cut at level 2 (2 mm), feed rate at level 1 (0.1 mm/rev) and cutting speed at level 1 (320 m/min).
- The most significant factor affecting the surface roughness was determined to be the feed rates (94.14 %) followed by the cutting speed (PCR: 0.10 %). However, the depth of cut has no effect on surface roughness.
- The empirical equations were developed and confirmation test were applied. The results obtained between experimental and predicted results have indicated a good agreement within the ranges of the applied cutting parameters.
- The large Taguchi model should be selected in the experimental works if a regression analysis is done.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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