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Analysis of the Effect of Tool Nose Radius, Feed Rate, and Cutting Depth Parameters on Surface Roughness and Cutting Force in CNC Lathe Machining of 36CrNiMo4 Alloy Steel

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Keywords

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Abstract

In this study, in turning 36CrNiMo4 steel, the effects of cutting parameters on surface roughness (***Ra***) value and main cutting force (***Fc***) were investigated. Tool nose radius (***R***), feed rate (***f***), and cutting depth (***a***) were used as machining parameters. The experiments were carried out at a constant cutting speed (***V***) of 150 m/min and under dry cutting conditions. Taguchi L9 orthogonal index was used in the design of the experiment, and the effect levels of processing parameters according to Signal to Noise (S/N) ratios and the relationship between them were analyzed using the analysis of variance (ANOVA) method for the analysis of the results. It was determined that the ***f*** was the most effective factor on the ***Ra*** value with 75.13% by contribution rate, and the best ***Ra*** value was obtained when 0.03 mm/rev ***f*** was used. It was determined that the most effective factor affecting the ***Fc*** was the ***a*** with a ratio of 62.39%, was determined that the ***Fc*** increased with the increase of the ***a***, the smallest ***Fc*** was obtained when the ***a*** was 0.05 mm.

Cite

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1. INTRODUCTION

36CrNiMo4 steel is frequently used in aerospace, automotive, and machinery industries. Some application requirements operating under high stresses and repeated loads require this steel. The most important features of 36CrNiMo4 steel are its ability to reach high hardness values and to have a high level of toughness. The machinability of this material at the desired quality and tolerances depends on the manufacturing method used and the optimization of the method parameters. Despite the other manufacturing methods developed, machining methods constitute a significant part of the industry (Puertas & Luis-Pérez, 2003; Kundrak et al., 2008). Turning, which is one of the machining methods, is one of the most used methods. The reason why the turning process is more preferred is that shapes with complex geometries can be manufactured with more precise tolerances in a single operation. Basic parameters in the turning process; ***f***, ***a***, and ***V***. The effects of ***Ra*** values of the cutting parameters at different rates (Korkut et al., 2007; Selvaraj & Philip, 2021). Dureja et al. (2014) analyzed the cutting parameters that affect the ***Ra*** value when turning hardened AISI D3 steel using a coated carbide tool. Their analysis as a result of the optimization of the cutting parameters stated that the factor affecting the ***Ra*** value the most was the ***f***. Thamizhmanii et al. (2007) found that the most influencing factor on surface quality in turning AISI 4140 steel is the ***a*** and the lower ***f*** provides better surface quality. In turning of AISI 4340 steel, ***Ra*** values decrease with low ***f*** (Rashid et al., 2016). Chou & Song (2004) reported that

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with increasing ***R***, a better ***Ra*** value is obtained, but it also causes an increase in the ***Fc***. Zerti et al. (2017) demonstrated the most significant effect on the ***Fc*** and the ***a*** is reported that the ***f*** that follows. Aouici et al. (2012) reported in their analysis that the ***a*** was statistically insignificant, but the ***Fc*** increased with increasing ***a***. Şahinoğlu & Rafighi (2020a) studied the machinability properties of the AISI 4140 material. In this experimental study, the influence of cutting parameters on vibrations, sound intensity, current value, and ***Ra*** value was investigated. From the results of the experiment, it was found that the most effective parameter for the ***Ra*** value is the ***f*** . Günay (2013) investigated the effect of AISI 316L cutting parameters on cutting force and ***Ra*** during turning. The experimental design with Taguchi L9 and the effects of cutting parameters with ANOVA were investigated. Gupta & Kohli (2014) Response Surface Method (RSM), ANOVA, and utilizing a mathematical model of AISI 4340 alloy steel turning operations have examined the ***Ra*** that occurred. In the results of working; affecting the ***Ra*** values have concluded that the ***f*** of the most important parameters. İynen et al. (2020a, b) analyzed the effect of cutting parameters on ***Ra*** and cutting forces using the Taguchi method in the turning process of AISI 4140 material. The effect levels of the cutting parameters were investigated using ANOVA.

In the presented work, the effect of constant cutting speed (*V*) and variable depth of cut (*a)*, feed rate (*f*) and nose Radius (*R*) on the surface roughness (*Ra*) and cutting force (*Fc*) was investigated during turning of 36CrNiMo4 alloy steel using VCMT inserts under dry cutting conditions. The design of experiment was performed according to the Taguchi method and the analysis of variance was performed to obtain the most significant parameters. In addition, the main effect plots show the impact of each cutting parameters on the response.

2. MATERIAL AND METHOD

The chemical composition of the 36CrNiMo4 steel used in the experimental study is shown in Table 1, the diameter of the steel is Ø70 mm and the turning operations were done in 20 mm lengths. A constant ***V*** of 150 m/min was used in the experiments. As machining parameters, ***a*** (0.05, 0.10, and 0.15 mm), ***f*** (0.03, 0.06, and 0.09 mm/rev) and as ***R*** (0.4 mm, 0.8 mm, and 1.2 mm) respectively VCMT 160404-SM, VCMT 160408-SM and VCMT 160412-SM inserts are used. The cutting inserts are connected to the lathe using AKKO TTJNL 2525 M16 barrel. The turning processes were done on the GOODWAY GS-260Y machine. During the turning process, the ***Fc*** was recorded using the KISTLER TYPE 9129AA dynamometer and the Kistler TYPE 5070 amplifier device. The test setup and the cutting tool used for chip removal are shown in Figure 1.

Table 1. *Chemical Composition of AISI 4340 Steel*

C (%)	Si (%)	Mn (%)	P_{max} (%)	S_{max} (%)	Cr (%)	Mo (%)	Ni (%)
0.34	0.32	0.63	0.032	0.033	1.45	0.24	1.55

Ra values of the machined parts were measured along 4.8 mm on the surfaces using the Mahr MarSurf PS 10 device. The experiments were carried out under dry processing conditions. The experiments were repeated three times and the average of the measurement results was recorded. Taguchi method was used to create the experimental set used for turning processes. Taguchi method is more powerful and easy to use than traditional methods. Designing experiments with the Taguchi method reduces the number of experiments and costs as well as saves time (Kirby et al., 2006). L9 experiment sequence was created using Minitab 16 program for three different levels of ***R***, ***f***, and ***a*** factors given in Table 2 with Taguchi method and experiment sequence is given in Table 3.

Table 2. *Processing Parameters and Levels*

Symbol	Unit	Level 1	Level 2	Level 3
R	mm	0.4	0.8	1.2
f	mm/rev	0.03	0.06	0.09
a	mm	0.05	0.10	0.15

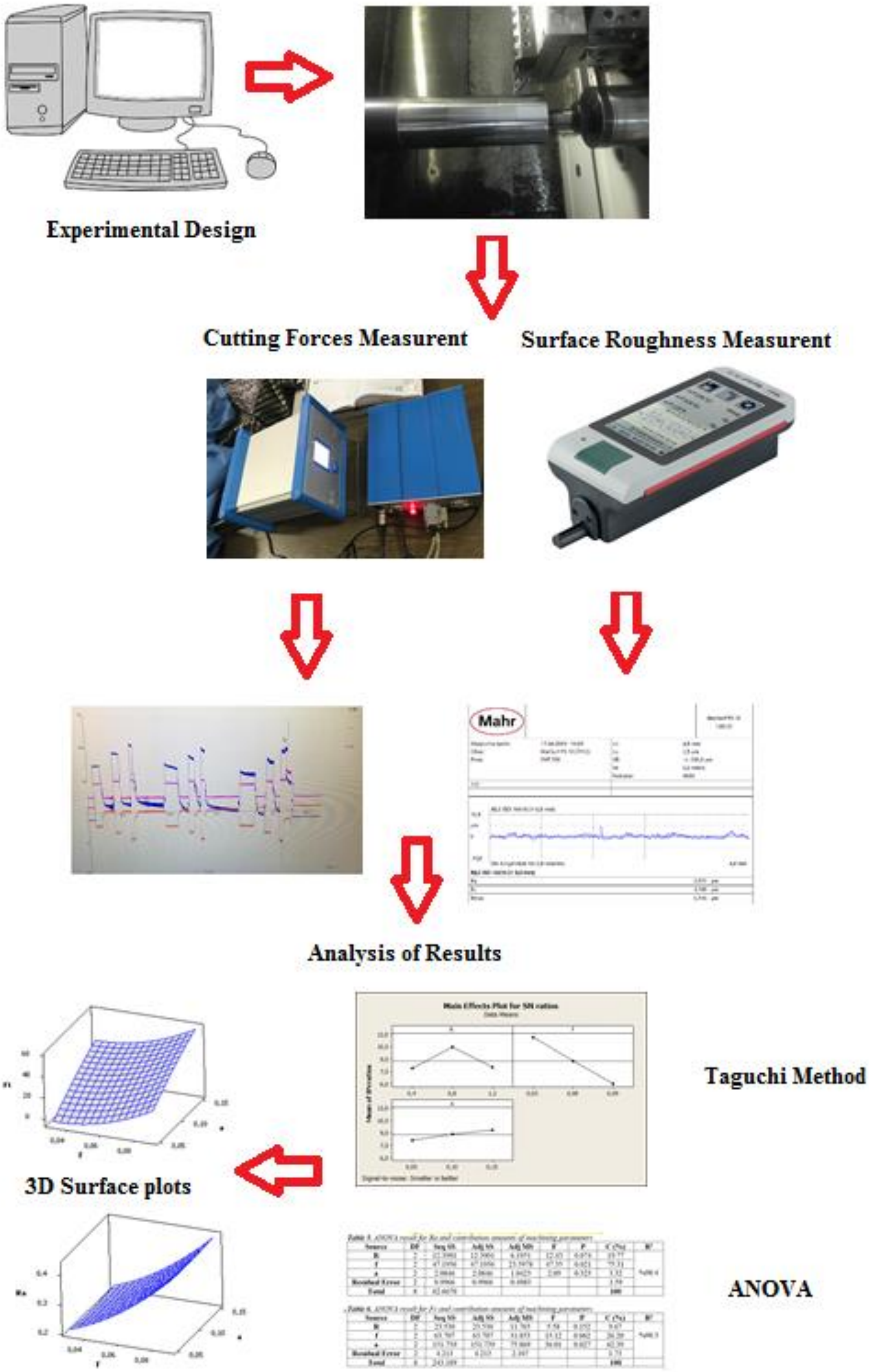

Figure 1. *Experiment Setup*

When analyzing with the Taguchi method, the S/N ratio is used to determine optimum levels. In the S/N ratio, the S term indicates the desired value (average) and the noise term (N) indicates the unwanted output value. In the Taguchi method, three basic criteria are used to evaluate S/N ratios; largest best, smallest best, and best rated. In this study, the optimum levels for optimum ***Ra*** are determined by using the "smallest best" criterion. The formulation used to calculate the S/N ratio is given in Eq. (1).

$$\frac{\mathbf{S}}{\mathbf{N}} = -10\log\frac{1}{n}\left(\sum y^2\right) \quad (1)$$

Table 3. *Experiment sequences*

Experimental No	Machining Parameters		
	R	**f**	**a**
1	0.4	0.03	0.05
2	0.4	0.06	0.1
3	0.4	0.09	0.15
4	0.8	0.03	0.1
5	0.8	0.06	0.15
6	0.8	0.09	0.05
7	1.2	0.03	0.15
8	1.2	0.06	0.05
9	1.2	0.09	0.1

3. RESULTS AND DISCUSSION

The results were obtained according to the average ***Ra*** and, ***Fc*** values. Taguchi method S/N ratios obtained as a result of the experiments depending on the cutting parameters are given in Table 4. S/N ratios showing the effect of machining parameters on ***Ra*** values are shown in Figure 2. When the figure is examined, it has been determined that the S/N ratios have the largest S/N ratios, respectively, the 1st level of the ***f*** (11.629 dB), the 2nd level of the ***R*** (10.448 dB), and the 3rd level of ***a*** (9.336 dB). The levels corresponding to these S/N ratios are respectively 0.03 mm/rev ***f***, 0.8 mm ***R***, and 0.15 mm ***a***. It is seen in the influence degree table that the most effective parameter on the ***Ra*** value is the ***f***. Secondly, the most effective value is the ***R*** and the ***a*** is in the last place in terms of the effect ratio. S/N ratios of the main forces measured during turning and the levels of machining parameters are shown in Figure 3.

The efficiency degrees of cutting parameters that affect the ***Fc*** are the ***a*** the ***f***, and the ***R***, respectively, from large to small. The S/N ratios of these values, respectively; The S/N ratio of the 1st level of ***a*** (-24.13 dB), the S/N ratio of the 1st level of the ***f*** (-26.43 dB), and the S/N ratio of the 2nd level of the ***R*** (-27.74 dB). Optimum cutting parameters were obtained at 0.05 mm ***a***, 0.03 mm/rev ***f***, and 0.8 mm ***R***.

Table 4. *Experimental results for Ra and Fc*

Ex. No.	R	f	a	Ra(µm)	Ra(dB)	Fc(N)	Fc(dB)
1	0.4	0.03	0.05	0.33	9.6297	10.70	-20.5877
2	0.4	0.06	0.10	0.39	8.1787	33.89	-30.6014
3	0.4	0.09	0.15	0.51	5.8486	65.76	-36.3592
4	0.8	0.03	0.10	0.21	13.5556	17.19	-24.7055
5	0.8	0.06	0.15	0.30	10.4576	39.24	-31.8746
6	0.8	0.09	0.05	0.43	7.3306	21.45	-26.6285
7	1.2	0.03	0.15	0.26	11.7005	50.12	-34.0002
8	1.2	0.06	0.05	0.42	7.5350	18.13	-25.1680
9	1.2	0.09	0.10	0.57	4.8825	61.59	-35.7902

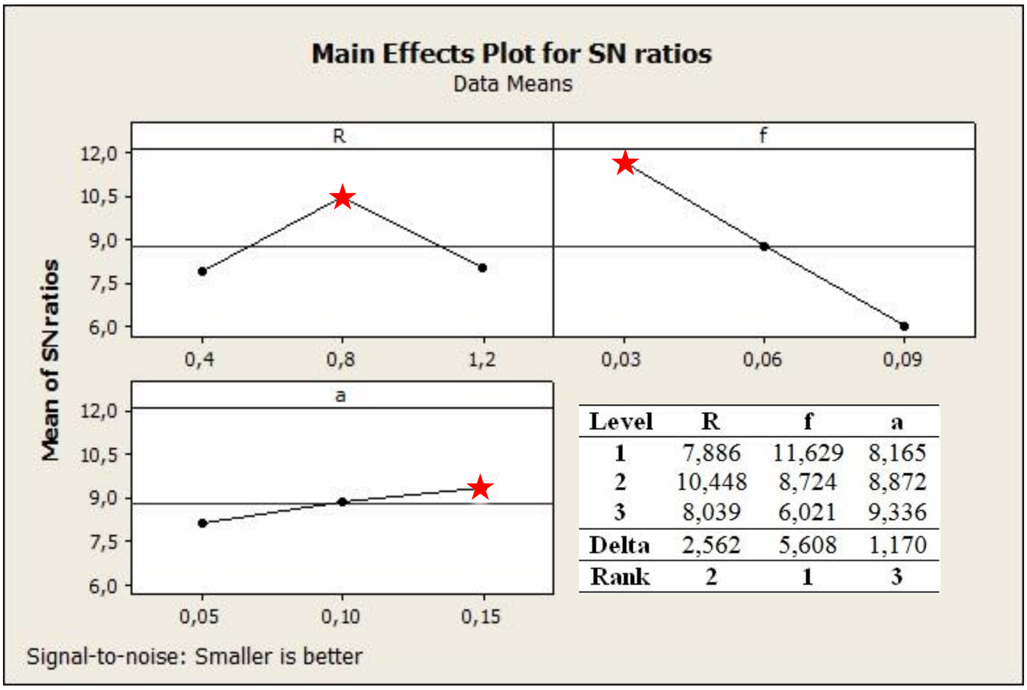

Figure 2. *Effect of machining parameters on Ra*

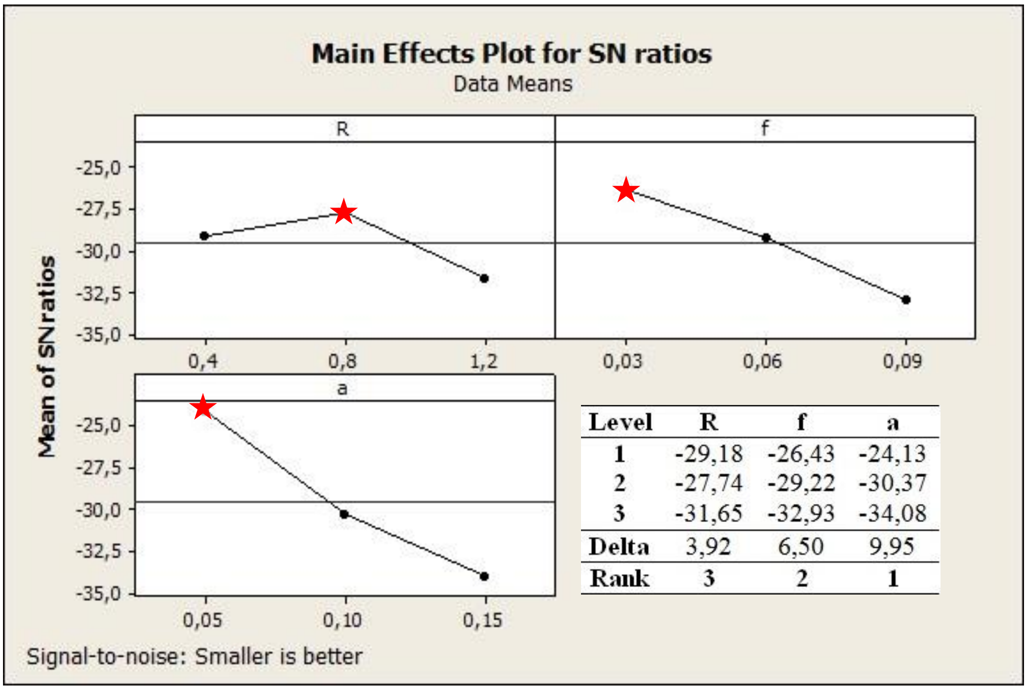

Figure 3. *Effect of machining parameters on Fc*

When Figure 4 is examined, it is seen that the ***Ra*** value increases with the increase in the ***f*** (Figure 4a). If the low ***f*** is even below the surface area required for minimum chip formation, the cutting tool mostly follows the surface without cutting the material and causes the material to flow in the horizontal direction (Thamma, 2008). At the same time, as the ***f*** increases, the number of chips removed per unit time increases, increasing ***Ra***. Some increase in ***R*** in Figure 4b and 4c provides a good surface quality, while a larger radius will reduce damping between tool and material, resulting in a worse surface quality (Beauchamp et al., 1996; Kishawy & Elbestawi, 1997). It is seen in Figure 4a-4b that as the ***a*** increases, the ***Ra*** value decreases. On the other hand, this combination provides some reduction in the ***Ra*** value, as it reduces the BUE formation together with low ***a*** and high ***V*** (Kwon & Choi, 2002; Thamma, 2008).

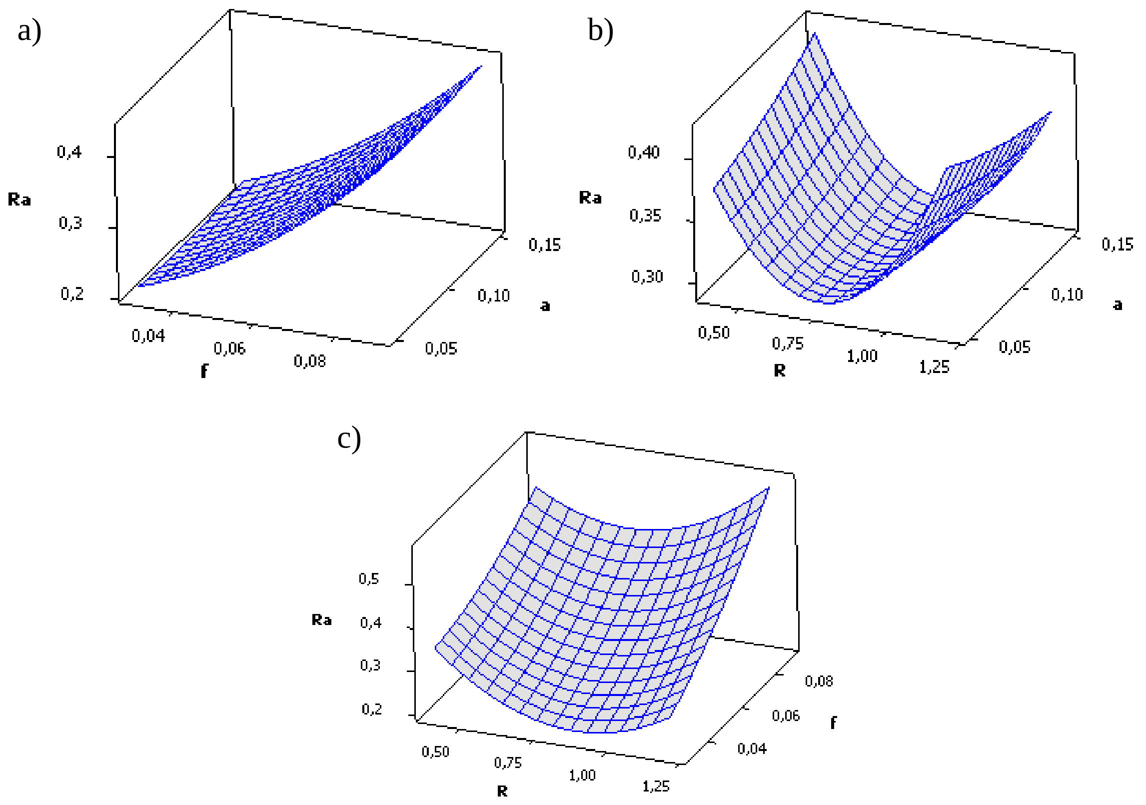

Figure 4. *3D graph of the relation of Ra with* ***a)*** *f-a,* ***b)*** *R-a,* ***c)*** *R-f*

The effect of cutting parameters on the ***Fc*** is shown in the surface graph in Figure 5 The ***Fc*** increases depending on the increase in the ***a*** and the ***f*** affecting the ***Fc*** (Figure 5a). Increasing the ***f*** and ***a*** will increase the contact area of the chip tool interface, thus increasing the cutting force (Bouacha et al., 2010). Also, the increase in the chip cross-sectional area as a result of the increase in the resistance of the material to rupture with the increase in the ***f*** caused an increase in the ***Fc*** (Saini et al., 2014) At the same time, as the ***f*** increases, the amount of chips removed per unit time increases, increasing the ***Fc***. The increase in the ***Fc*** with the increase in the ***f*** and ***a*** can be explained by the Kienzle equation. Here, the chip cross-sectional area, which increases due to the increase in the ***f*** and ***a***, causes the cutting forces to increase (Çakır, 2000). When looking at the relationship between the ***R*** and the ***Fc*** in Figure 5b and 5c, it is seen that the minimum cutting force value is obtained at 0.8 mm ***R***. Thamma stated in his study that as the area required for the formation of minimum chip thickness decreases as the ***R*** increases, there is an increase in the ***f*** and ***Fc*** (Thamma, 2008). As a result of the machining experiments observed, the increase in the ***a*** and the ***f*** increases the ***Fc*** and ***Ra*** value, which is parallel to the studies in the literature, and the same determinations have been obtained in studies using different materials and different cutting tools in the literature (Nalbant et al., 2007; Motorcu, 2010; Asiltürk & Neşeli, 2012; Gürbüz et al., 2017; Mia et al., 2017; Koçak, 2020; Şahinoğlu & Rafighi, 2020b).

The contribution amounts (***C***) of machining parameters and levels to the ***Ra*** value were evaluated by performing an ANOVA, the results are shown in Table 5. According to the analysis results, 75.31% ***f***, 19.77% ***R***, 3.32% ***a*** affect the ***Ra*** value, respectively. In the light of the data shown in Table 5, considering the significance value of $p<0.05$, it was determined that the ***R*** and ***a*** parameters were not significant in terms of semantic ratio, and the ***f*** was significant. The effective rates of machining parameters on the ***Fc*** are shown in Table 6. When the table is examined, it has been determined that the contribution rates are respectively 62.39% a, 26.20% ***f***, and 9.67% ***R***. In terms of semantic ratio ($p<0.05$), it was determined that ***R*** and ***f*** were not significant, but ***a*** was significant. The test results are above 95% for the ***Ra*** value and the ***Fc*** according to the error rates shown in Table 5 and Table 6.

Table 5. *ANOVA result for Ra and contribution amounts of machining parameters*

Source	DF	Seq SS	Adj SS	Adj MS	F	P	C (%)	R^2
R	2	12.3901	12.3901	6.1951	12.43	0.074	19.77	%98.4
f	2	47.1956	47.1956	23.5978	47.35	0.021	75.31	
a	2	2.0846	2.0846	1.0423	2.09	0.323	3.32	
Residual Error	2	0.9966	0.9966	0.4983			1.59	
Total	8	62.6670					**100**	

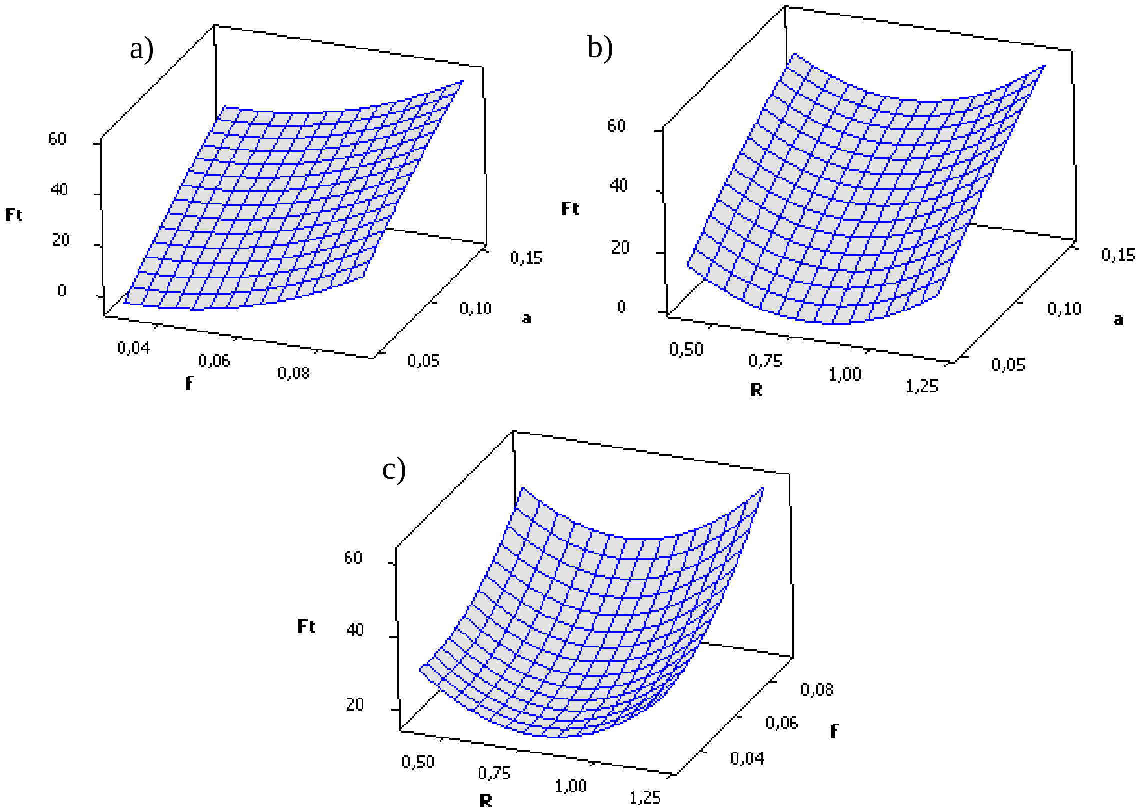

Figure 5. *3D graph of the relation of Fc with **a)** f-a, **b)** R-a, **c)** R-f*

Table 6. *ANOVA result for Fc and contribution amounts of machining parameters*

Source	DF	Seq SS	Adj SS	Adj MS	F	P	C (%)	R^2
R	2	23.530	23.530	11.765	5.58	0.152	9.67	%98.3
f	2	63.707	63.707	31.853	15.12	0.062	26.20	
a	2	151.739	151.739	75.869	36.01	0.027	62.39	
Residual Error	2	4.213	4.213	2.107			1.73	
Total	8	243.189					**100**	

Since optimum values obtained according to Taguchi S/N ratios were not included in the Taguchi L9 experiment set, verification experiments were needed. Therefore, 0.8 mm ***R*** (R2), 0.03 mm/rev ***f*** (f1), and 0.15 mm ***a*** (a3) parameters were determined as optimum cutting parameters for ***Ra*** and ***Fc***. The experiments were repeated 3 times and the arithmetic mean of the results was obtained. Experimental and predicted values obtained after verification tests are shown in Table 7. The ***Ra*** between the experimental data and predicted values is 93.10% when the table is examined, it was found that the ***Fc*** close relationship is 86.32%.

Table 7. *Optimization Test Results for Fc and Ra*

Factor	Level	Fc (N)		Ra (µm)	
R2	0.8	Prediction	Experimental	Prediction	Experimental
f1	0.03	33.36	38.53	0.216	0.232
a3	0.15				

4. RESULTS

In the study, the relationship between process parameters namely, ***R***, ***a***, ***f*** and responses such as ***Ra*** and ***Fc*** were investigated in the turning process of 36CrNiMo4 steel.

• There is a proportional relationship between ***f*** and ***Ra***. With the increase in the ***f***, the roughness value also increases.

• Considering the highest S/N ratios of the factors affecting the ***Ra*** value according to the "smallest best" criterion, the values corresponding to these levels were determined to be 0.03 mm/rev ***f***, 0.8 mm ***R***, and 0.15 mm ***a***, respectively.

• According to ANOVA analysis, 75.31% ***f***, 19.77% ***R***, and 3.32% ***a*** affect the ***Ra*** value.

• In terms of semantic ratio, it was concluded that ***R*** and ***a*** are not significant for ***Ra*** value according to p<0.05.

• It was determined that the cutting parameters that affect the ***Fc*** are the ***a***, the ***f***, and finally the ***R***, respectively, from large to small. The contribution levels of the ***Fc*** as% of the ***a***, ***f***, and ***R*** parameters were determined as 62.39%, 26.20%, and 9.67%, respectively.

• When the effect of cutting parameters on the ***Fc*** was examined in terms of semantics, it was seen that only *a* was significant.

• It was determined that the ANOVA results of the parameters affecting the surface roughness value and the main cutting force were above the 95% confidence level.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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