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Optimization of Cutting Parameters Affecting Cutting Force and Surface Roughness in Machining of AISI P20 Die Steel

[1] Mahir Akgün, [2] Barış Özlü

[1]Department of Machine and Metal Technology, Technical Sciences Vocational School, Aksaray University, Aksaray, Turkey
Corresponding author, e-mail: mahirakgun@aksaray.edu.tr

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Abstract - This study focuses on optimizing cutting parameters effective on cutting force (Fc) and surface roughness (Ra) in the machining of AISI P20 steel. The turning experiments have been performed in CNC lathe at three different cutting speeds (Vc) (120, 180, and 240 m/min), three different feed rates (f) (0.12 0.21 and 0.3 mm/rev), and three different depths of cut (a) (0.4, 0.8, and 1.2 mm) according to Taguchi L9 orthogonal array. The effect levels of the cutting parameters on Fc and Ra have been determined with analysis of variance (Anova). The analysis results indicate that the depth of cut is the most significant parameter affecting Fc while the feed rate is the most significant parameter affecting Ra. Moreover, the result analysis shows that cutting speed of 240 m/min, feed rate of 0.12 mm/rev, and depth of cut of 0.4 mm) factor levels were the optimum cutting parameters for the output parameters (Fc and Ra). In turning experiments performed at optimum cutting parameters, the lowest Fc and Ra values were measured as 178N and 0.412 µm, respectively.

Keywords: AISI P20 steel, Cutting Force, Surface Roughness, Optimization

AISI P20 Kalıp Çeliğinin İşlenmesinde Kesme kuvveti ve Yüzey Pürüzlülüğünü Etkileyen Kesme Parametrelerinin Optimizasyonu

Öz- Bu çalışma, AISI P20 çeliğinin işlenmesinde kesme kuvveti (Fc) ve yüzey pürüzlülüğü (Ra) üzerinde etkili olan kesme parametrelerinin optimize edilmesine odaklanmaktadır. Tornalama deneyleri Taguchi L9 ortogonal dizisine göre üç farklı kesme hızında (Vc) (120, 180 ve 240 m/dak), üç farklı ilerleme hızında (f) (0.12 0.21 ve 0.3 mm/dev) ve üç farklı talaş derinliğinde a) (0,4, 0,8 ve 1,2 mm) CNC torna tezgahında gerçekleştirilmiştir. Kesme parametrelerinin Fc ve Ra üzerindeki etki düzeyleri varyans analizi (Anova) ile belirlenmiştir. Analiz sonuçları, talaş derinliğinin kesme kuvvetini etkileyen en önemli parametre olduğunu, ilerleme hızının ise yüzey pürüzlülüğünü etkileyen en önemli parametre olduğunu göstermektedir. Dahası, analiz sonuçlar, 240 m/dk kesme hızı, 0.12 mm/dev ilerleme hızı ve 0.4 mm talaş derinliği çıktı parametreleri (Fc ve Ra) için optimum kesme parametreleri olduğunu göstermektedir. Optimum kesme parametrelerinde yapılan tornalama deneylerinde en düşük Fc ve Ra değerleri sırasıyla 178N ve 0.412 µm olarak ölçülmüştür.

Anahtar kelimeler: AISI P20 çelik, Kesme kuvveti, Yüzey Pürüzlülüğü, Optimizasyon

[1] Corresponding author: Tel: 0 382 288 20 16
E-mail: mahirakgunaksaray.edu.tr

1. Introduction

In today's conditions, many mass-produced parts are created using molds and mold elements. In particular, considering the use of thermoplastics, the importance of the molding sector is understood. Moreover, the quality, cost and lead times of molds are critical to the economics of many industries. For example, in the automotive industry, it affects produce a large number of components, subassemblies, and assemblies. Therefore, it focuses on process modeling, rapid prototyping, rapid tooling, high-speed cutting and optimized toolpath creation for hard machining with the developing technology in this field [1, 2].

AISI P20 steel, which is plastic mold steel, is used in applications such as plastic extrusion, plastic injection, and blow molding. The very important properties of these steels are hardness, strength, high toughness, very good polishability, weldability, and suitability for nitration. However, the formation of built-up edge (BUE) in the machining process of this steel seriously affects the cutting tool life and production efficiency [3]. Moreover, it is difficult to machine these steels, which are alloyed with strong carbide forming elements such as Mo and Cr [4]. on the other hand, in the mold manufacturing industry, it is desired to produce the molds with the best surface quality in a short time. Therefore, in order to obtain high cutting performance in mold production, optimum levels of cutting parameters should be selected. However, cutting conditions are generally determined by an operator's experience or practical knowledge [5]. Tooling cost and time loss are increased in this way. For these reasons, it is very important to define the most suitable cutting conditions in terms of surface quality and cutting forces, which are essential machinability criteria for production efficiency [6-9]. For example, Davim was investigated the effect of cutting parameters and cutting time on drilling metal-matrix composites using the Taguchi method [10]. Statistical results indicate that the cutting time was the factor which had the greatest influence on the tool wear (50%), followed by the feed rate (24%). Mandal et al. were investigated the machinability of AISI 4340 steel with newly-developed zirconia-toughened alumina ceramic inserts [11]. The Taguchi method, the signal-to-noise ratio, and analysis of variance have been applied to study the performance characteristics. Statistical results indicate that the depth of cut is a maximum contribution to tool wear. Akkuş and Yaka applied the Taguchi method to investigate the effect of cutting parameters on turning AISI 1040 steel [12]. The analysis of the results showed that feed rate had the most significant effect on surface roughness. Ballıkaya and Altuğ were used the Taguchi method to determine the optimal process parameters in machining hardened D2 cold work tool steel using wire erosion (WEDM) method [13]. The orthogonal array, the signal-to-noise ratio, and analysis of variance were employed to study the performance characteristics (the machined surface hardness and the regenerated white layer thickness). Statistical results indicate that the most effective parameter on the white layer thickness is the commercial and heat-treated sample parameter (57.236%). In the cut surface hardness values, the most effective parameter was the sample parameter (98.627%). Akkuş and Yaka, investigated the effect of cutting parameters on surface roughness, vibration, and energy consumption in the machining of titanium 6Al-4V ELI (grade 5) alloy [14]. The analysis of the results showed that the effective parameter in surface roughness, vibration and energy consumption is feed rate.

From the literature review, it is seen that optimization techniques are used to estimate output parameters and optimization of input parameters in machining operations (turning, milling, drilling, etc.). Furthermore, it has been determined that the studies on the machinability of AISI P20 plastic mold steel are limited. In the present study, the machinability of AISI P20 mold steel, which is widely used in the mold industry, was evaluated in terms of main cutting force (Fc) and surface roughness (Ra). Machinability tests were carried out on a CNC lathe according to the Taguchi L9 index. S/N analysis and analysis of variance were used to determine ideal cutting conditions and the effects of cutting parameters on output parameters (Fc and Ra), respectively.

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2. Materials and Methods

In the study, AISI P20 steel with a diameter of 30 mm and a length of 300 mm was used as the workpiece material. Table 1 shows the chemical composition of the workpiece material used in the experiments. Turning experiments were performed on Johnford TC-35 CNC lathe under dry cutting conditions. Kistler 9257A type dynamometer and equipment's were used to measure the main cutting force (Fc). Force measurement system; it consists of 9257A dynamometer, Kistler 5070A amplifier, data acquisition card, and "DynoWare Type 2825Ai-2" software for collecting cutting force signals. The experimental setup is schematically shown in Fig. 1. In the analysis of cutting forces, the main cutting force (Fc) values, which are of primary importance in terms of energy consumption in machining operations, were taken into account.

Table 1. Chemical composition (%) of the workpiece material

Elements	C	Si	Mn	Cr	Ni	Mo
Wt.%	0.1	0.3	2.5	3.00	1.0	0.3

In the turning experiments, carbide cutting tools, which were coated with TiCN/Al2O3 using the CVD method and produced by Kennametal in KCM15 quality and CNMG120408UP geometry, were used. The turning parameters and levels used in the experiments are given in Table 2. Roughness measurements were made on the machined surfaces using the MAHR-Perthometer-M1 portable surface roughness (Ra) device. After each measure, the workpiece was rotated 90º on its axis, and the average Ra value was determined by taking the arithmetic average of the four measurements.

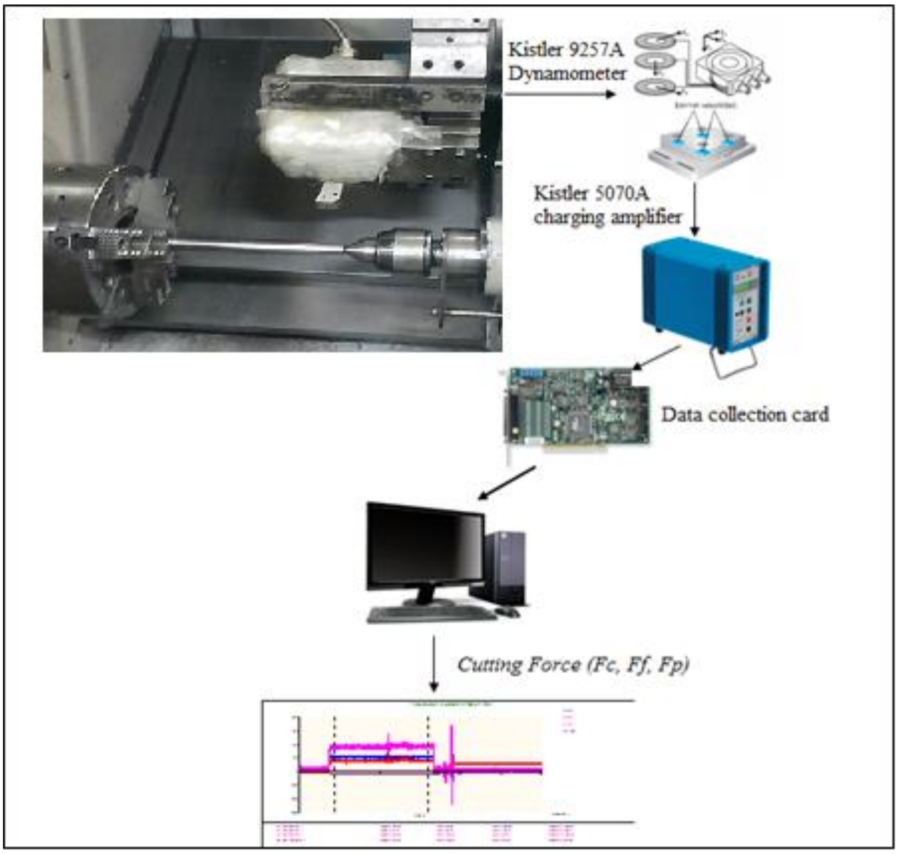

Figure 1. Experimental setup used for the measurement of cutting force

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Table 2. Cutting parameters and levels.

Code	Cutting Parameters	Units	Level 1	Level 2	Level 3
A	Cutting speed (Vc)	(m/min)	120	180	240
B	Feed rate (f)	(mm/rev)	0.12	0.21	0.3
C	Depth of cut (ap)	(mm)	0.4	0.8	1.2

3. Experimental Design and Optimization

In the manufacturing industry, different optimization methods are used in material processing to minimize product costs and increase efficiency [15]. Taguchi method, which is one of the optimization methods, is used to reduce the product development time and the relative costs [16]. In this study, Taguchi method was used in designing the experiments and determining the optimum cutting parameters. In this context, turning experiments were designed according to Taguchi's L9 (3^3) orthogonal array and the signal-to-noise (S/N) ratio was calculated to determine the optimum cutting parameters [17]. The "smallest best" approach in Eq. (1) was used to calculate the signal-to-noise (S/N) ratios because it was aimed to determine the optimum cutting parameters to obtain the lowest levels of Fc and Ra in the study.

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

Moreover, analysis of variance (ANOVA) was applied to determine the effects of cutting parameters on the main cutting force (Fc) and surface roughness (Ra) values.

4. Results and Discussions

4.1 Analysis of the signal-to-noise (S/N) ratio

Cutting force (Fc) and surface roughness (Ra) have been measured in experiments designed by using the Taguchi technique, optimization of the measured output parameters has been provided by signal-to-noise (S/N) ratios. The lowest values of Ra and Fc are significant for improving the product's quality and the dynamics of the machine tool, respectively. For this reason, the “lower-the-better” equation was used for the calculation of the S/N ratio. Table 3 shows the Fc and Ra values obtained after processing and their corresponding S/N ratios. At the end of the turning tests, the average values of the Fc and Ra have been calculated to be 230.07N and 0.668 µm respectively. Similarly, average values of S/N ratio for surface roughness and flank wear were calculated to be -48.2 dB and 3.583 dB respectively.

Table 3. Experiment results and S/N ratios values

Id No	Experiment Code	Fc (N)	SN-Fc (N)	Ra (µm)	SN-Ra (µm)
1	$A_1B_1C_1$	218.50	-46.789	0.550	5.1927
2	$A_1B_2C_2$	275.00	-48.786	0.670	3.4785
3	$A_1B_3C_3$	332.62	-50.438	0.765	2.3267
4	$A_2B_1C_2$	240.55	-47.604	0.620	4.1521
5	$A_2B_2C_3$	272.54	-48.691	0.720	2.8533
6	$A_2B_3C_1$	315.47	-49.977	0.765	2.3267
7	$A_3B_1C_3$	185.98	-45.343	0.650	3.7417
8	$A_3B_2C_1$	230.05	-47.234	0.500	6.0206
9	$A_3B_3C_2$	284.35	-48.943	0.780	2.1581

Analysis of the effect of each input factor (Vc, f, ap) on the output parameters was performed with a “S/N response table”. The response tables of S/N for Ra and Fc are given in Table 4. According to

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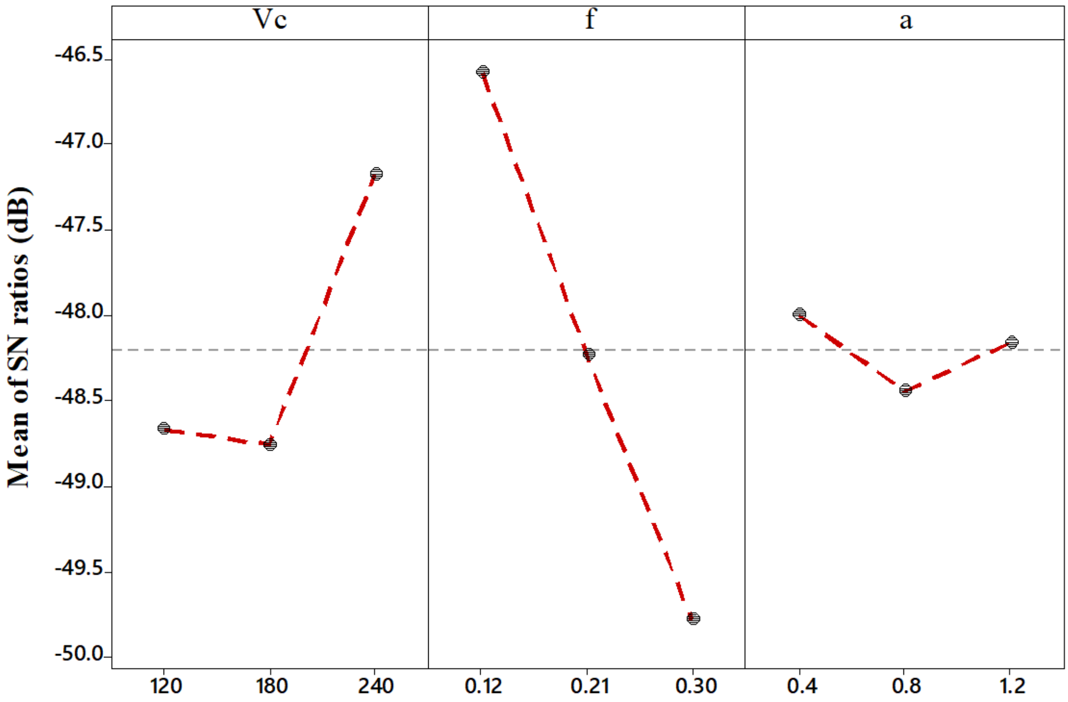
Research Article / Araştırma Makalesi

Table 4, A cutting speed 240 m/min (level 3), B feed rate 0.12 mm/rev (level 1) and C depth of cut 0.4 mm (level 1) were defined as ideal cutting parameters for both Fc and Ra. In turning experiments performed at optimum cutting parameters, the lowest Fc and Ra values were measured as 178N and 0.412 µm, respectively. In a similar study, Gupta et al. reported that cutting speed of 160 m/min, nose radius of 0.8 mm, feed of 0.1 mm/rev, depth of cut of 0.2 mm and the cryogenic environment were the most favorable cutting parameters for high-speed CNC turning of AISI P-20 tool steel [18].

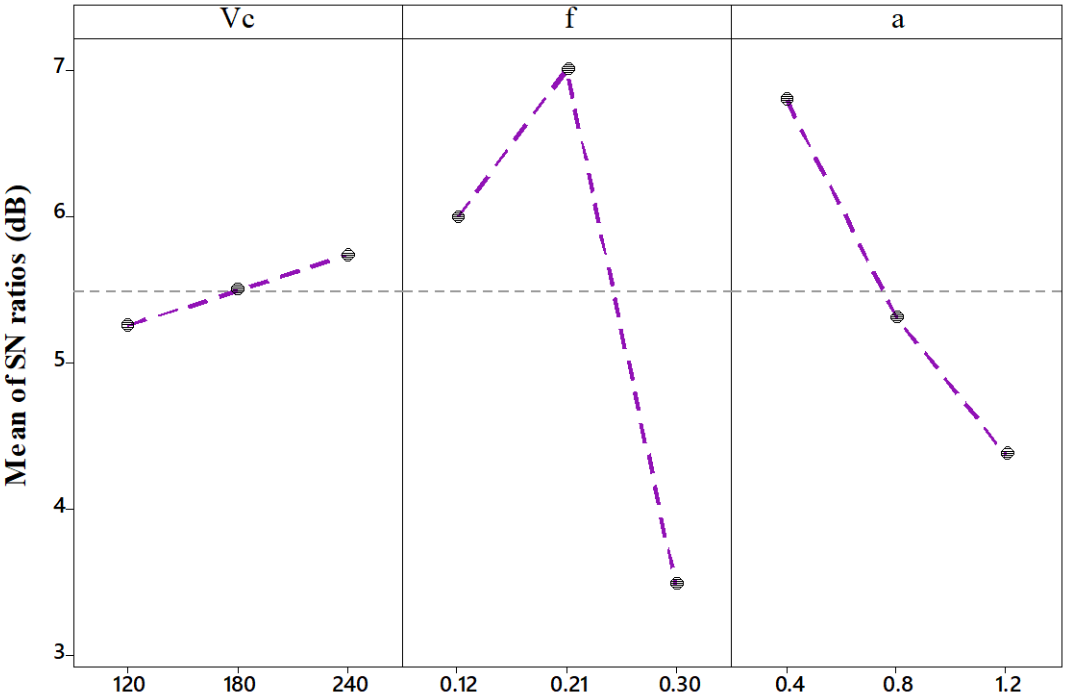
Table 4. Answer table for Fc and Ra

Code	Factors	Level 1	Level 2	Level 3	Delta	Rank
Fc						
A	Vc	-48.67	-48.76	**-47.17**	1.58	2
B	f	**-46.58**	-48.24	-49.79	3.21	1
C	ap	**-48.00**	-48.44	-48.16	0.44	3
Ra						
A	Vc	3.666	3.111	**3.973**	0.863	3
B	f	**4.362**	4.117	2.271	2.092	1
C	ap	**4.513**	3.263	2.974	1.539	2

The graphic form of the level values of the control factors for Fc and Ra is shown in Figure 2. When Figure 2 is examined, it is seen that the output parameters (Fc and Ra) increase with increasing feed rate and depth of cut and decrease with increasing cutting speed.



(a)



(b)

Figure 2. Effect of process parameters on average S/N ratio for a) Fc and b) Ra.

4.2 Evaluation of experimental results

The changes in the Fc and Ra obtained as the result of the experimental study are seen in Figs. 3 and 4, respectively. The measured Fc values ranged from 150 to 320N, and the measured Ra values ranged from 0.4098 to 1.626 µm. When Figs. 3 and 4 is examined, it is seen that the Fc and Ra increases depending on the increase in the feed rate in the machining of AISI P20 steel. The Fc values are about 35% increase with increasing feed rate from 0.1 mm/rev to 0.15 mm/rev while 45% increase by feed rate from 0.15 mm/rev to 0.2 mm/rev. Similarly, The Ra values are about 40% increase with increasing feed rate from 0.1 mm/rev to 0.15 mm/rev while 50% increase by f from 0.15 mm/rev to 0.2 mm/rev. The experimental findings showed that the highest Fc and Ra values were measured at the highest level of the feed rate (0.2 mm/rev). Another indicator of the significant effect of the feed rate on the output parameters is the 76.10% and 59.39% contribution rates for Fc and Ra in the ANOVA analysis, respectively. It is thought that this situation is caused by the increase in the loads on the cutting tool as a result of the increase in the chip cross-section due to the increase in the feed rate [19-21]. When the tool wear images in Fig. 5 are examined, it is seen that the nose and flank wear increases with the increase in the feed rate. Consequently, this deformation in the cutting tool affects the output parameters negatively. Similarly, Yaşar et al. in the experimental and numerical analysis of cutting force in the turning of AISI P20 reported that Fc increased with the increase in feed rate [22]. On the other hand, it can be said that the Fc and Ra values slightly decrease with the increase in cutting speed. However, there is no significant change with increasing cutting speed at high feed rates (0.21 mm/rev and 0.30 mm/rev). Aggarwal et al. in turning AISI P20 tool steel using liquid nitrogen as a coolant reported that for low cutting force and surface roughness, a high cutting speed range (160-200 m/min) and a low to medium feed rate range (0.10-0.12 mm/rev) should be selected [23].

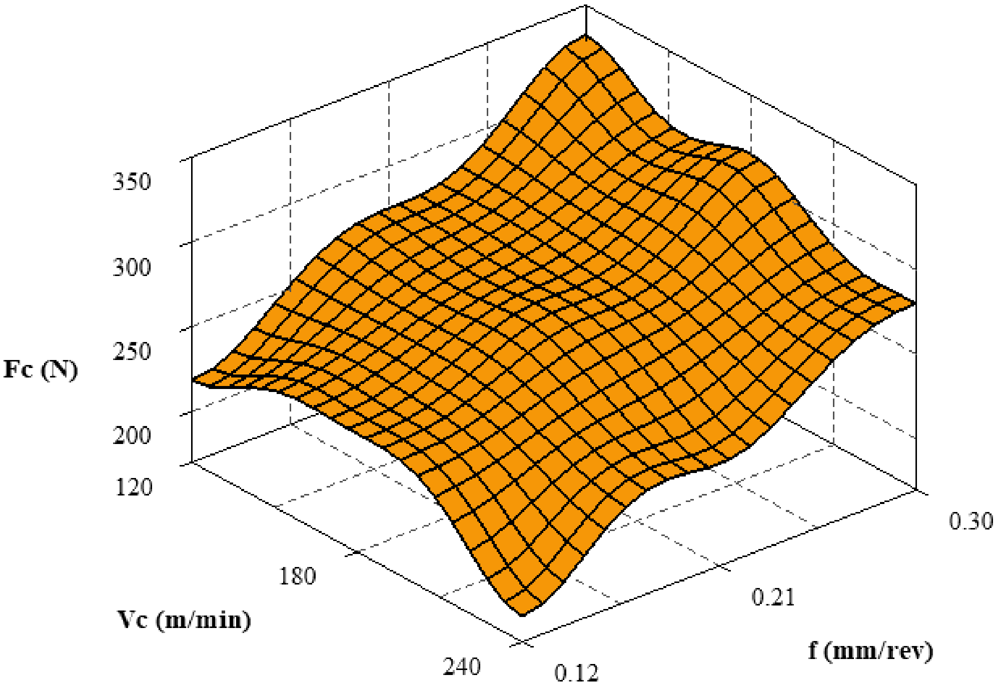


Figure 3. Effect of cutting parameters on Fc

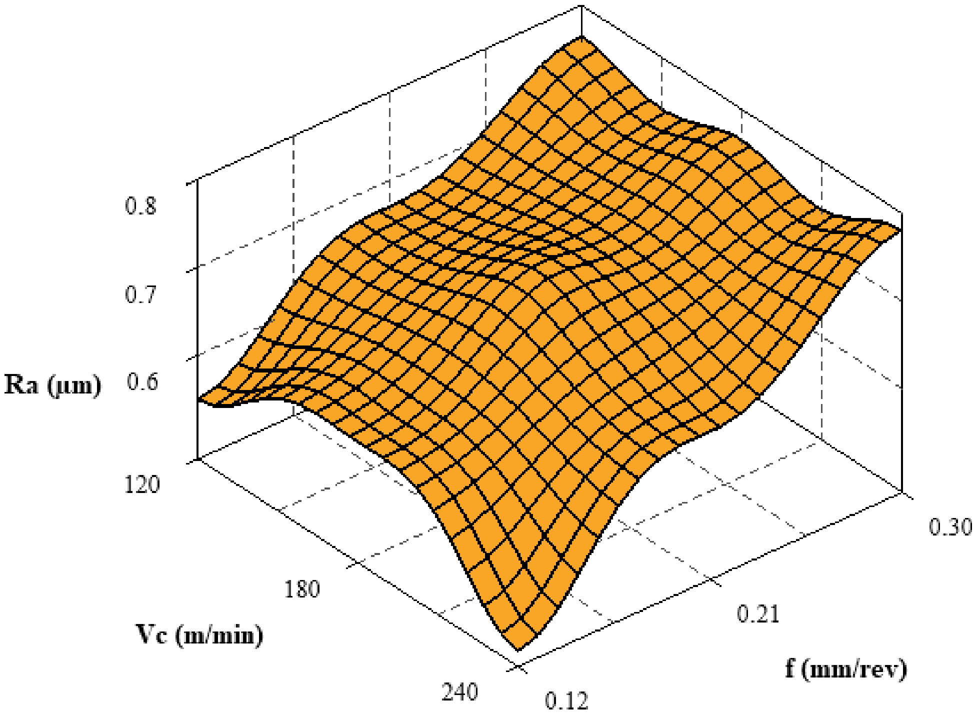


Figure 4. Effect of cutting parameters on Ra

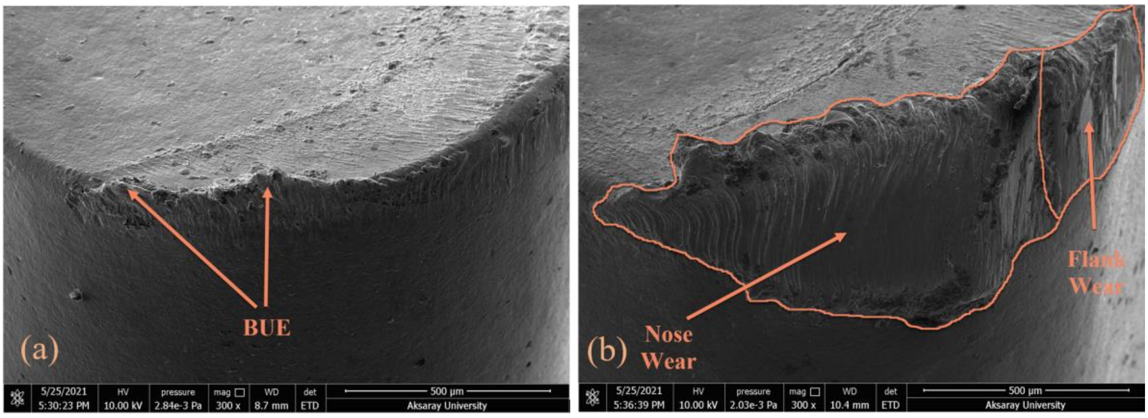


Figure 5. SEM images of cutting tools (a) 240 m/min, 0.12 mm/rev and 0.8 mm depth of cut (b) 240 m/min, 0.30 mm/rev and 0.8 mm depth of cut

4.3 Analysis of variance (ANOVA) results

ANOVA was used to analyze the effects of cutting speeds, feed rates, and depths of cut on output parameters (Fc and Ra). The ANOVA results for the output parameters (Fc and Ra) are shown in Table 5. This analysis was carried out a 5% significance level and a 95% confidence level. In the table, F values and percentage contribution rate were used to determine the importance of each factor on the output parameters. Considering the F values, the factor with the largest F value is most influences the output parameter. According to Table 5, the percent contributions of the Vc, f and ap factors on the Fc were found to be 21.74%, 76.10%, and 1.04%, respectively. Consequently, the most important parameter affecting the Fc was feed rate (factor B, 76.10%). On the other hand, the percent contributions of the Vc, f and ap factors on the Ra were found to be 6.77%, 59.39%, and 24.19%, respectively. This showed that the most effective factor on Ra was feed rate (factor B, 59.39%). The percent of error was considerably low at 1.24% and 9.65% for Fc and Ra, respectively.

Table 5. Variance results for Fc and Ra

Factors	DF	Seq SS	Adj MS	F-Value	P-Value	Contribution (%)
Fc						
Vc	2	3857.6	1928.81	19.35	0.049	21.74
f	2	13507.6	6753.53	67.75	0.015	76.10
ap	2	184.1	92.05	0.92	0.520	1.04
Error	2	199.4	99.68	-	-	1.12
Total	8	17748.1	-	-	-	100.00
Ra						
Vc	2	0.00533	0.00266	0.7	0.588	6.77
f	2	0.04682	0.02341	6.16	0.140	59.39
ap	2	0.19072	0.00953	2.51	0.285	24.19
Error	2	0.00760	0.00380	-	-	9.65
Total	8	0.07883	-	-	-	100

5. Conclusions

In this study, an experimental investigation was performed to analyze the effects of the cutting parameters on surface roughness (Ra) and cutting force (Fc) in the machining AISI P20 steel. Moreover, the optimum cutting conditions were determined by the Taguchi method. The following conclusions may be drawn from this study:

- Generally, with increasing feed rate, the surface roughness and the main cutting force (Fc) values were increased.

- According to the S/N ratios, it was concluded that the A3B1C1 (cutting speed 240 m/min, feed rate 0.12 mm/rev, and depth of cut 0.4 mm) factor levels were the optimum cutting parameters for the main cutting force and surface roughness. In turning experiments performed at optimum cutting parameters, the lowest Fc and Ra values were obtained as 178N and 0.412 µm, respectively.
- The variance results indicate that the depth of cut was the parameter affecting the main cutting force while the feed rate was the most significant factor affecting surface roughness with a percentage contribution of 74.6% and 59.39%, respectively.
- Medium cutting velocity and feed rate could be recommended for use in the turning of AISI P20 plastic mold steel.

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