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Evaluation of tool radius and machining parameters on cutting forces and surface roughness for AA 6082 aluminum alloy

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Abstract: In this study, the effects of machining parameters on surface roughness and cutting forces during the machining of AA6082 aluminum alloy, which is widely utilized in automotive, manufacturing and aerospace industries, on a conventional lathe were investigated. Tool corner radius (0.4 mm and 0.8 mm), depth of chip (0.25-0.5 mm), feed rate (0.1-0.2 mm/rev) and cutting speed (65-105 m/min) were used as input variables. Surface roughness and cutting forces were evaluated as outputs; effective parameters and optimum process conditions were determined by analysis of variance (ANOVA) and S/N ratios. The results show that tools with a corner radius of 0.8 mm provide lower cutting forces and better surface quality, and the study provides practical optimization data for the machinability of AA6082 alloy, making original contributions to both academic literature and industrial applications.

Keywords: AA 6082; machinability; turning; surface roughness; cutting force; ANOVA.

1. Introduction

In the manufacturing sector, it is common to encounter areas where materials that do not contain any other metal in their composition are used, but alloys have a much stronger place. Each alloy has its own unique properties that put it ahead of others. This can sometimes be corrosion resistance, sometimes casting ability, sometimes mechanical properties, etc. The inherent recyclability and reusability of aluminum without any loss of properties gives it a head start in manufacturing processes over less economical materials such as steel [1]. In addition, being a material that offers both lightness and durability, it is used as a substitute for steel in many engineering applications. This results in not only pure aluminum but also alloyed aluminum becoming more and more common in many sectors. AA6082, an alloy of the aluminum, which is the most easily machined of non-ferrous metals, is widely preferred due to its low density, lightness, low cost, high strength (the highest strength of the 6000 series alloys), high corrosion resistance and its structure that allows forging [2-4]. This material may not respond well to machinability due to its high thermal expansion coefficients and tendency to form build-up edges, as well as its poor ductility [5]. At this point, the priority needs in the machining process, which is a multifaceted process where many factors such as cost effectiveness, quality, applicability, cutting force, energy consumption, tool wear, surface quality, production speed, maintenance are effective, should be analyzed, and the process should be brought to a state that will meet these needs with optimum parameter/level selections. Machining is a multifaceted process influenced by numerous factors such as cost effectiveness, surface quality, tool wear, energy consumption, production speed, and maintenance requirements. A key component of machining optimization involves modeling and analyzing the relationship between input parameters (such as cutting speed, feed rate, depth of cut, and tool geometry) and output responses (such as cutting force, surface roughness, material removal rate, and tool life). Optimization approaches such as S/N ratios as well as statistical methods such as ANOVA and multi-criteria decision-making tools play an important role in the development of robust prediction models for machining processes. These methods allow the systematic evaluation of factor influences, interaction effects, and identification of optimal parameter settings for achieving desired machining outcomes. General machining processes are turning, milling, drilling, grinding, reaming, honing, rolling, forging, casting, etc., and turning is responsible for an average of 45% of the workload caused by such machining processes [6]. Therefore, a literature

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summary of machining processes, primarily turning, involving AA6082 alloy is presented below.

In the study by Saravanan and Mahendran [3], the machinability of AA6082 alloy produced with boron carbide (B4C) reinforcement at different weight percentages was investigated by computer numerical control (CNC) turning process. In the study, which presented evaluations in terms of tool wear and surface roughness at the center of depth of cut, feed rate and cutting speed it was reported that boron carbide reinforcement improved the machinability. Jebaraj, Pradeep Kumar [4] conducted a study to evaluate the impact of machining parameters, one being cooling media (dry, wet, cryogenic CO_2 and cryogenic LN_2) on surface finish, tool wear and cutting forces during milling of 6082-T6 alloy. It was emphasized that while the best machining performance is obtained with wet cooling, cryogenic cooling can extend tool life by preventing high temperature generation but at the same time, it can compromise tool wear. The study by Yapan, Türkeli [5] is an example of the use of minimum quantity lubrication (MQL) processes using GNP-added nanofluid (N-MQL) in the milling of Al6082 alloy. In the study where the cutting temperature, force, feed force, roughness and chip morphology as well as carbon emission and total processing cost were evaluated, it was found that the use of N-MQL improved all parameters compared to dry cutting and MQL. In the study by Chowdhury, Das and Chakraborty [6], the effects of parameters such as cutting speed, feed rate and depth of cut on machinability and surface quality in CNC turning operations of Aluminum 6082-T6 alloy were analyzed using Fuzzy multi-criteria decision-making methods. While it was reported that decision-making methods can be used as a powerful tool for the optimization of parameters, it was stated that the material is suitable for machinability in CNC. Singh, Chauhan [7] aimed to reduce the roughness of the surface resulting from the machinability of Al-6082 T-6 on a CNC lathe in their study. It was observed that there is a ranking among the parameters in terms of their effects on roughness as follows: speed, feed rate, depth of chip. Turan et al. [8] investigated the effects of tool coating, cutting speed and feed rate on surface roughness and geometric tolerances in dry drilling of Al 6082-T6 alloy. The experimental results showed that uncoated tools gave the lowest surface roughness, while TiAlN coated tools gave the lowest cylindricity error. They also reported that among the prediction models, the Artificial Neural Network (ANN) achieved the highest accuracy. Işık et al [9] fabricated AlSi10Mg samples by selective laser melting (SLM) and investigated the effects of scanning distance (SD), scanning speed (SS) and laser power (P) as fabrication parameters on quality outputs such as surface roughness, diameter change, circularity change and concentricity. According to the results obtained, the increase in laser power improved the roughness and diameter change, while the increase in scanning distance and scanning speed had negative effects on circularity and concentricity; moreover, the most suitable production parameter combination was determined as A2B1C3 (0.10 mm, 1450 mm/s, 370 W) by the gray relationship analysis (GRA) method. According to ANOVA analysis, it was determined that the most effective parameter on surface roughness was laser power with a rate of 53.22%. Özlü [10] investigated the effects of cutting speed and feed rate on cutting forces and surface roughness in turning Sleipner cold work tool steel. Increasing feed rate increased the forces and roughness, while higher cutting speeds decreased these values. As a result of the experiment, the lowest cutting force and the best surface finish were obtained with a cutting speed of 150 m/min and a feed rate of 0.1 mm/rev. Binali et al [11] investigated the effects of cutting speed, feed rate, chip depth and cutting media parameters on surface roughness, cutting force and tool wear in the machining of Al6082 alloy. They concluded that the nano-SiO_2-doped olive oil-based MQL method showed superior performance by providing the lowest cutting force, temperature and surface roughness values. The results reported that nano-doped biobased MQL systems offer an effective alternative for sustainable and highly efficient machining.

Kartal, Yerlikaya and Gökkaya [12] studied the extent to which the machining of Al-6082 T6 aluminum alloy by abrasive water jet (AWJ) method causes changes in terms of surface roughness and macro surface characteristics. As a result of the evaluation carried out for different levels of cutting parameters such as distance, abrasive flow rate, spindle speed and nozzle feed rate, it was found that the most effective parameter on surface quality was the nozzle feed rate.

Stanojković and Radovanović [13] investigate the effects of the parameters of speed, feed and depth of chip on the force, moment and surface roughness during the milling process of AA-6082-T6 alloy. As a result of the experiments studied out using solid carbide end mills, it was suggested that the order of importance in terms of their effects are depth of chip, feed and speed.

In this study, Varatharajulu, Duraiselvam [14] evaluated the impact of processing parameters during surface milling of AA-6082 alloy. In the study where the depth of chip, feed and spindle speed parameters were taken as reference, evaluations were made on the roughness, material removal rate and processing time. It was reported that with the correct combination of spindle speed, feed and depth of chip, roughness and processing time could be brought to the best level. The study by Garcia, Feix [15] is about the finish turning of 6082-T6 aluminum alloy with an uncoated carbide tool under dry and reduced quantity lubricant (RQL) conditions. The study showed that the use of RQL was superior to the dry condition by reducing both surface roughness and tool wear. Beșliu and Tamașag [16] evaluated the impact of cooling and cutting conditions on surface quality during machining of AA6082-T6 aluminum alloy. Although the MQL method gives better results than dry conditions, it was stated that the results obtained at some feed rates are not stable. In this study,

Table 1. Chemical composition-AA 6082 [23]

Element	%Al	%Fe	%Cu	%Mn	%Mg	%Cr	%Ni	%Zn	%Ti	%Ga	%V	%Si
% weight	96.5	0.47	0.1	0.55	1.15	0.17	0.013	0.09	0.019	0.012	0.017	0.85

Quintana, Gomez [17] evaluated the impact of feed and tool diameter used in milling operations of aluminum 6082 alloy on cycle time, forces, roughness and dimensional accuracy. One of the study results is that the best surface quality and dimensional accuracy are obtained when low feed rate and large diameter cutting tools are used. Yigit [18] investigated the effect of coolant/lubricant medium on tool wear, cutting forces and surface roughness during machining of 6082 aluminum alloy at different cutting speeds. Compared to dry cutting, MQL stood out with lower wear and longer life. Patel and Deshpande [19] studied the effects of machining parameters on surface roughness (Ra) and material removal rate (MRR) in turning process of aluminum 6082 alloy. It is emphasized that the optimum parameters for the lowest roughness and the highest metal removal rate are 1.5 mm corner radius, 0.142 mm/rev feed rate, 1235 rpm spindle speed. Solanki and Jain [20] studied on the effect of process parameters speed, feed and depth of chip on response variables-Material Removal Rate (MRR) and Surface Roughness (Ra) for aluminum-6082 material. It was stated that the most effective parameters were feed for roughness and depth of chip for MRR. The study by Aydın [21] is about the changes in cutting force and cutting power at depths of cut lower than the tool nose radius during turning of AA6082-T4 aluminum alloy. It has been shown by both Finite Element Analysis and Experimental study that chip depth has a considerable impact on forces and speed has a considerable impact on power. In the study investigating the optimization of cutting parameters on surface roughness and material removal rate (MRR) in turning process of Aluminum Alloy 6082 (AA6082), Aryan, John [22] reported that spindle speed is one of the most effect parameters on MRR and roughness. Although these studies have provided valuable insights, a comprehensive analysis combining the effects of tool nose radius with detailed cutting parameters on both surface roughness and cutting forces under conventional dry turning conditions remains limited.

The aim of this study was to evaluate the effect of various machining parameters on cutting forces and surface roughness in machining AA 6082 aluminum alloy using 0.8 and 0.4 corner radius cutting tools. In the literature, some important gaps have been observed in the studies on the machinability of AA6082 aluminum alloy. While only the effect of machining parameters is commonly evaluated, this study provides a broader perspective by taking into account the significant effect of tool corner radius. In this context, the data obtained can be a direct reference for both academic research and industrial applications. In this research, the effects of different levels of cutting speed and feed parameters were investigated according to a full factorial experimental design and ANOVA analysis and (S/N) ratios were utilized to determine the best turning environments.

2. Materials and Methods

2.1. Workpiece Material

AA 6082 aluminum alloy (Seykoç, Kocaeli, Turkey) with a length of 500 mm and a diameter of 50 mm, which is widely used among alloys, was utilized as the workpiece material in the experimental study. The chemical characteristics of the workpiece are shown in **▶Table 1** and the physical and mechanical properties are given in **▶Table 2**.

Table 2. Physical and Mechanical Properties of AA6082 Alloy [23]

Property	Value
Tensile Stress (Mpa)	310
Yield Stress (Mpa)	285
Length (%)	10
Hardness ($Hv_{0.2}$)	115

2.2. Experiments, Cutting Tools and Cutting Parameters

Cutting tools were selected in accordance with ISO 3685 with TiC coated CCMT 09T308-304 and CCMT 09T304-304 (Korloy, Seoul, Republic of Korea) series cutting tools according to the widely preferred applications in the manufacturing industry [24]. In accordance with the purpose of the experiment and according to the hypothesis established by examining the studies in the literature, the parameters were selected taking into account both the suggestions of the tool company and the material properties. Tools were changed in each run of the machining experiments. The cutting-edge length is 9 mm, the cutting tool clearance angle was 7° degrees and the insert thickness was 4.97 mm. Two different types of cutting tools were used, with a corner radius of 0.8 mm and a corner radius of 0.4 mm. In the cutting experiments, a full factorial experimental design was utilized to determine the speed, feed and depth of chip parameters/levels. Full factorial experimental design is considered to be an optimal approach as it evaluates all possible combinations of cutting parameters given a small number of factors [25-27]. The first step in designing the study is to determine the processing parameters that could effect the responses. After determining the parameters with their levels, the experimental design was created for all possible combinations. In the next step, the specified parameter and level combination was tested and the experimental results were evaluated. When ▶**Table 3** shows the determined processing parameters with their levels, ▶**Figure 1** shows an overview of the study.

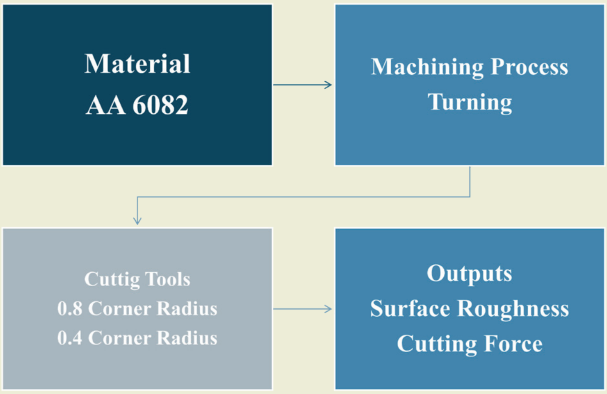

Figure 1. Overview of the study

Table 3. Experiment parameters

Exp. No	Cutting Speed	Feed Rate	Chip Depth
	(m/min)	(mm/rev)	(mm)
1	65	0.1	0.25
2	105	0.1	0.25
3	65	0.1	0.5
4	105	0.1	0.5
5	65	0.2	0.25
6	105	0.2	0.25
7	65	0.2	0.5
8	105	0.2	0.5

As seen in the literature, the “smaller is better” approach for the S/N ratio is preferred for quality characteristics where it is desired to keep the obtained measurement values at the lowest level [28]. When determining the optimum levels of machining parameters, the values of cutting force and surface roughness should be the smallest in order to increase productivity. Therefore, in the calculation of the S/N ratios, the objective function of the “smaller is better” case of the performance characteristic given in Eq.1 was used.

$$S/N = -10log\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \quad (1)$$

ANOVA was applied to the experimental results at 95% (α=0.05) confidence level to determine the effect levels of machining parameters on force and roughness. Optimization studies and variance analysis were carried out with the help of Minitab program.

1.1. Measurement of Cutting Forces and Surface Roughness of Machine Tool

A total of 16 machining experiments were studied out using a conventional De Lorenzo S547-8899 lathe available at Selcuk University Faculty of Technology. Table 4 presents specifications of it. Forces were measured with a KISTLER 9275 dynamometer (Kistler Instrumente AG, Winterthur, Switzerland). For the cutting forces, the force values obtained during cutting were averaged and recorded in the computer environment. After the experiment, the surface roughness values were measured from three different points with a measuring length of 5.6 mm using a Mahr Perthometer M1 (Mahr, Göttingen, Germany) device and evaluated by averaging them. Surface roughness measurements are customized according to DIN EN ISO 4287. In light of all this, Figure 2 shows a graphical summary of the experimental process.

Table 4. Specification of lathe

Features	Value
Maximum workpiece diameter	460 mm
Distance between chuck and tailstock	1500 mm
Spindle speed range	25-1800 rev/min
Spindle speed number	12 piece
Feed range	0.04 -2.46 mm
Number of feeds	122 piece
Maximum tool holder size	25x25 mm
Motor power	5.5 kW

3. Results and Discussions

Cutting experiments were carried out on conventional lathe with 0.4-0.8 mm corner radius cutting tool forms depending on the variation in machining parameters. The surface roughness values on the machined parts and the cutting forces generated during machining were measured and the parameters effecting these values and their relationships with each other were interpreted.

3.1. Evaluation of Surface Roughness

The average roughness values in microns obtained from turning tests with cutting tools coded CCMT 09T308-304 and CCMT 09T304-304 with machining parameters were given graphically in ▶**Figure 3**. In ▶**Figure 3**, the first parameter that drawed attention in general was the feed rate; it has been seen that the roughness increased with the increase in the feed. This result can be explained by utilizing the ideal roughness equation given in Eq. 2 [29, 30]. As can be seen from the equation expressed as surface roughness (Ra: µm), feed rate (f: mm/rev) and tool corner radius (r_ε: mm), surface roughness and feed were directly proportional to each other. In other words, the variation in feed rate directly effected the roughness of the surface. The main reason for this was that at low feed rates, the amount of chips removed

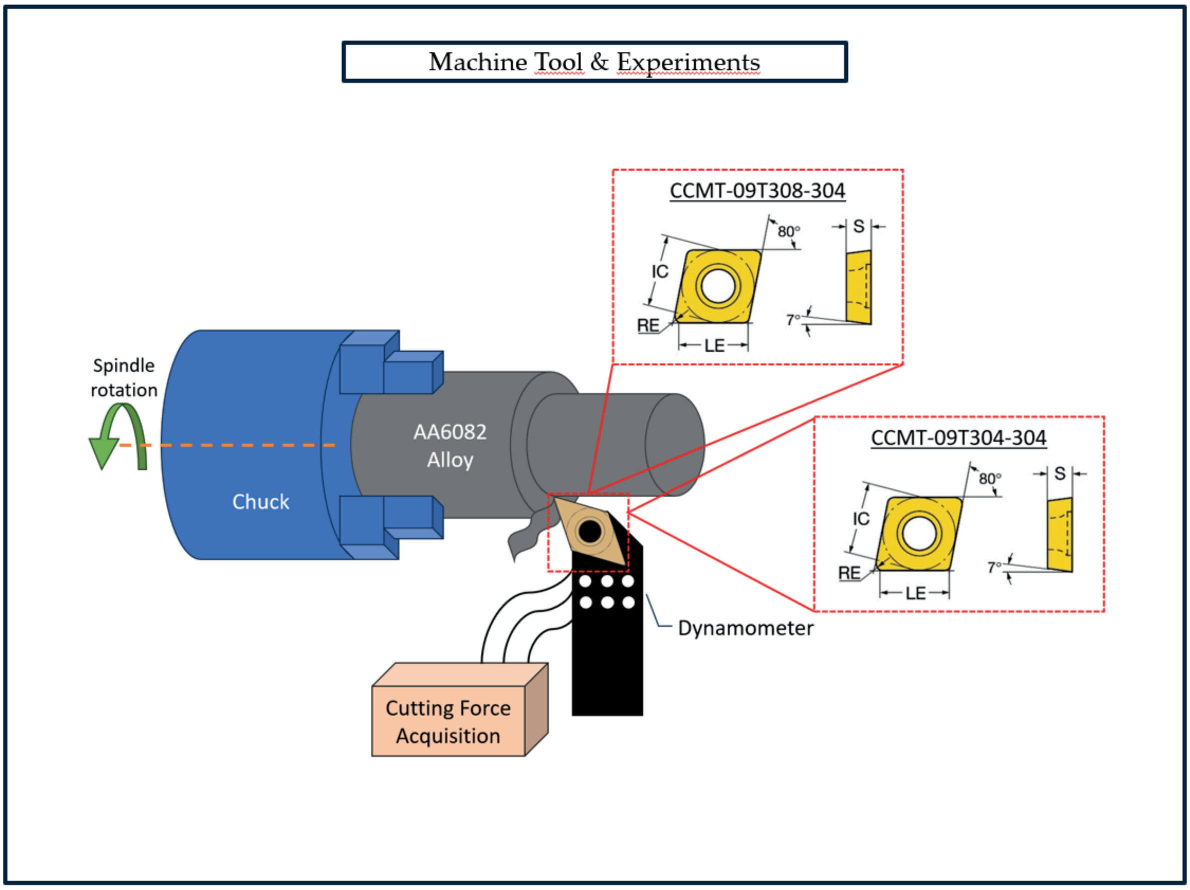

Figure 2. Graphical summary of the experimental process

by the cutting tool per feed rate was small and the surface was machined more smoothly, whereas when the feed increased, the tool removed larger chips and larger grooves were formed on the surface and these groove caused an increase in the roughness of the part surface [31-34]. In addition, this can increase the friction between the workpiece and the cutting tool, leading to heat build-up in the machining zone and an increase in wear and a decrease in cutting tool life, resulting in faster cutting edge deterioration, reduced machining capability and undesirable surface finish [35-37]. It has been observed from the graph that the roughness increased with increasing feed rate for both tools with 0.8 and 0.4 corner radius. The best surface quality was observed on surfaces machined with 0.8 corner radius cutting tools and the worst surface quality was observed on surfaces machined with 0.4 corner radius cutting tools. This was since when machining high feed rates with a small corner radius tool, the cutting tool contacts the workpiece more and increases the cutting forces. It was thought that the tool with a corner radius of 0.4 causes more deterioration on the workpiece surface than the tool with a corner radius of 0.8, as a result of high vibration formation with increasing cutting forces [38].

$$R_a = \frac{0.0321 \times f^2}{r_\varepsilon} \tag{2}$$

It has known that the increase in temperature in the cutting zone with the increase in speed was among the factors that facilitate chip flow. However, the effect of temperature more than the expected levels was thought to cause plastic deformation on the surface of the material in AA 6082 aluminum alloy. Therefore, it can be concluded that the deformation reflects negatively on the surface structure and worsens the surface quality. Similar experimental results were found in the literature [39-42]. However, in a study, it was reported that the most effective cutting parameter on roughness values was cutting speed and according to the analysis results, it was stated that the most effective parameter with the highest contribution rate on surface roughness was again cutting speed [43]. In another study, it was emphasized that the surface roughness value decreased with increasing cutting speed, and it was stated that the chip-to-tool contact length shortened with the increase in cutting speed, and as a result, deformations decreased [44]. Looking at the roughness graph in this study, it was observed that the increase in speed had a negative effect on the surface quality in the results of the experiments performed with two different corner radiuses. As can be seen in the graph, the lowest roughness occurred in the experiments with two corner radius at a cutting speed of 65 m/min. It can also be seen from the graph that machining with a 0.4 corner radius cutting tool produces more roughness on the surface than machining with a 0.8 corner radius cutting tool. The reason for this was thought to be that the 0.8 mm corner radius distributes the cutting forces better and provides a smoother surface compared to smaller corner radius [45, 46]. In a study on the turning of AA 6082 T4 alloy [47], the corner radius of the cutting tools were determined as 0.4 mm and 0.8 mm and it was found that the cutting forces were distributed more evenly, especially in tools with 0.8 mm corner radius.

When the graph has been interpreted to evaluate the effect of the depth of cut on surface roughness, it has been seen that surface roughness improves as depth of cut increases. In ductile materials such as AA 6082 aluminum alloy, it was thought that the probability of chip sticking (BUE) occurring was high when the depth of cut was low. In the literature, it was quite possible to come across studies where this situation caused irregularities on the surface and results in undesirable surface quality [48, 49]. However, in this study, it can be said that when the depth of cut is increased, chip removal becomes more controlled and BUE formation, i.e. sticking to the tool edge, decreases and as a result, a smoother surface is obtained. In the experiments with 0.4 and 0.8 corner radius, as can be seen in the graph, improvements in surface roughness occurred with increasing the depth of cut. However, contrary to the other studies, in the machining with 0.4 corner radius, the roughness increased slightly on the surface when the speed of 105 m/min, 0.2 mm/rev feed was changed from 0.25 mm chip depth to 0.5 mm chip depth under the same conditions. This is thought to be due to the fact that small corner radius make it difficult to break chips at high chip depths, which leads to undesirable chip agglomeration and worsens the surface quality [50]. According to the graphical evaluation results of the turning experiments performed with cutting speed, feed rate, chip depth and 0.4-0.8 corner radius tool, machining with 0.8 corner radius tool produced better surface quality on AA 6082 aluminum material.

The S/N ratio is called the quality characteristic that constitutes the main decision mechanism. The S/N ratio, an analysis specific to the statistical technique, is the ratio of a signal sampled with humidity and ambient temperature to the background noise factor. [51-53]. By calculating the S/N ratio, the optimum machining parameters can be estimated [54-58]. Since the surface roughness value was desired to be minimum, S/N ratios were calculated according to the *smaller is better* property. The analysis result graphs were given in ▶**Figure 4** and ▶**Figure 5** for tools with 0.8 and 0.4 corner radius, respectively. When the S/N ratios graph for 0.8 corner radius was analyzed in ▶**Figure 4**, it was understood that the factor with the largest change for roughness was feed (0.1, 0.2 mm/rev). The feed factor was followed by the cutting speed and chip depth factors. The least change was observed in the chip depth factor (0.25, 0.5 mm). A similar situation has been also valid for the S/N ratios graph for 0.4 corner radius given in ▶**Figure 5**. When the S/N ratios graph was analyzed, the biggest change between the ratios was seen in the feed rate factor and the change in the chip depth factor was the lowest. ANOVA analysis has been used to determine whether the independent variable has a significant effect on the dependent variables [59]. As a result of the analysis for surface roughness, ANOVA analysis was performed to see the influence of the factors.

The results of the analysis for 0.8 and 0.4 corner radius were given in ▶**Table 5** and ▶**Table 6** respectively. When the ANOVA analysis for 0.8 corner radius were analyzed in ▶**Table 5**, it has been seen that the feed rate and cutting speed factors were statistically significant for S/N ratios ($p<0.05$), but the chip depth factor wss

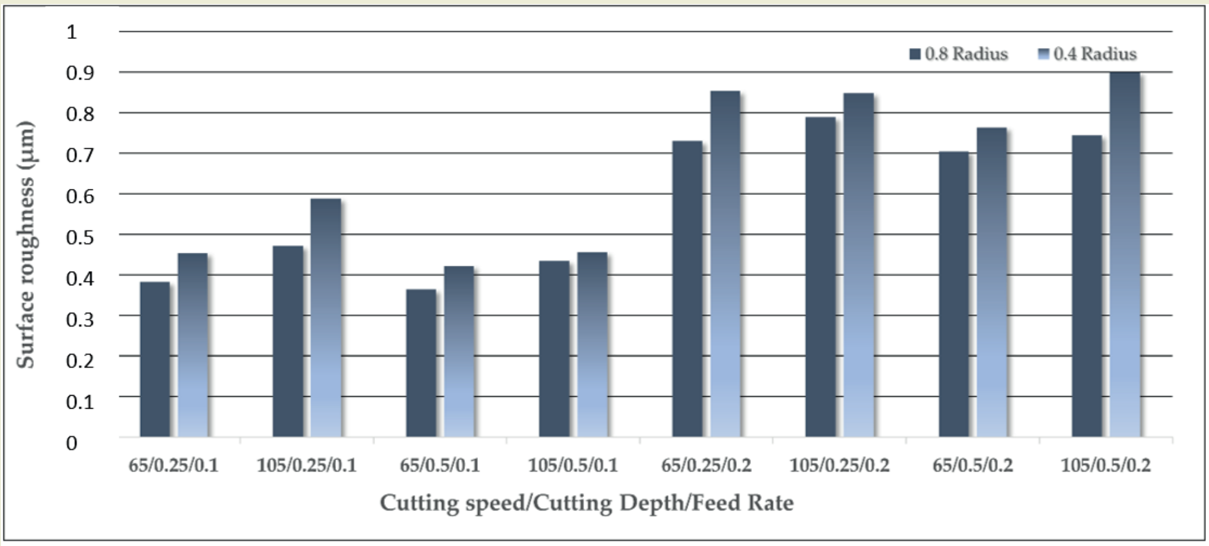

Figure 3. Surface roughness variation vs. cutting speed, chip depth and feed rate

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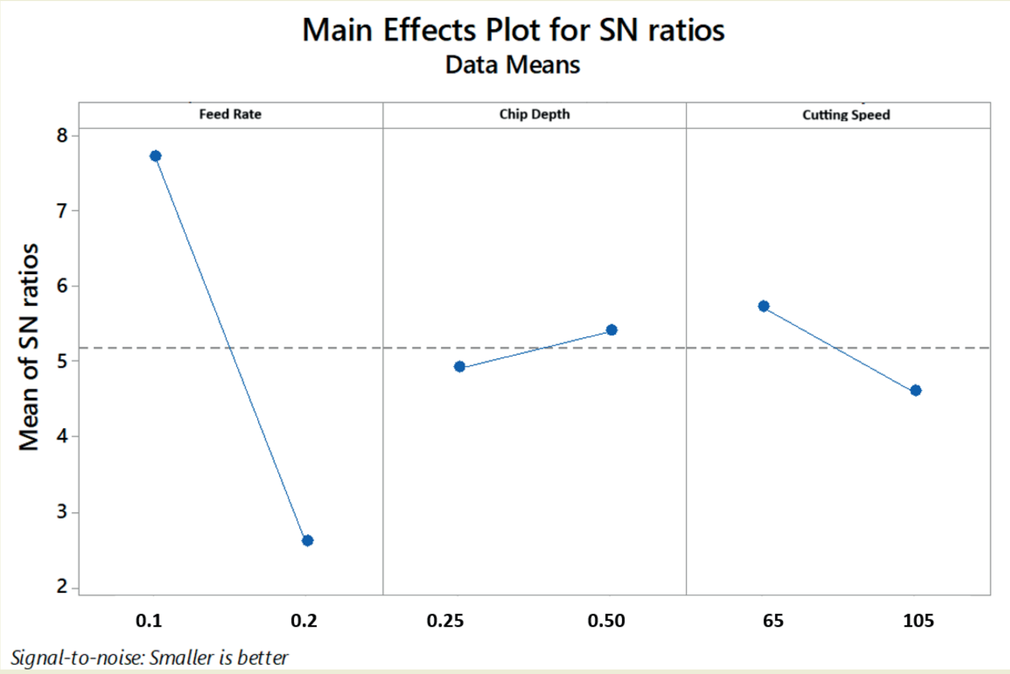

Figure 4. Main effects of S/N ratios for surface roughness – 0.8 corner radius

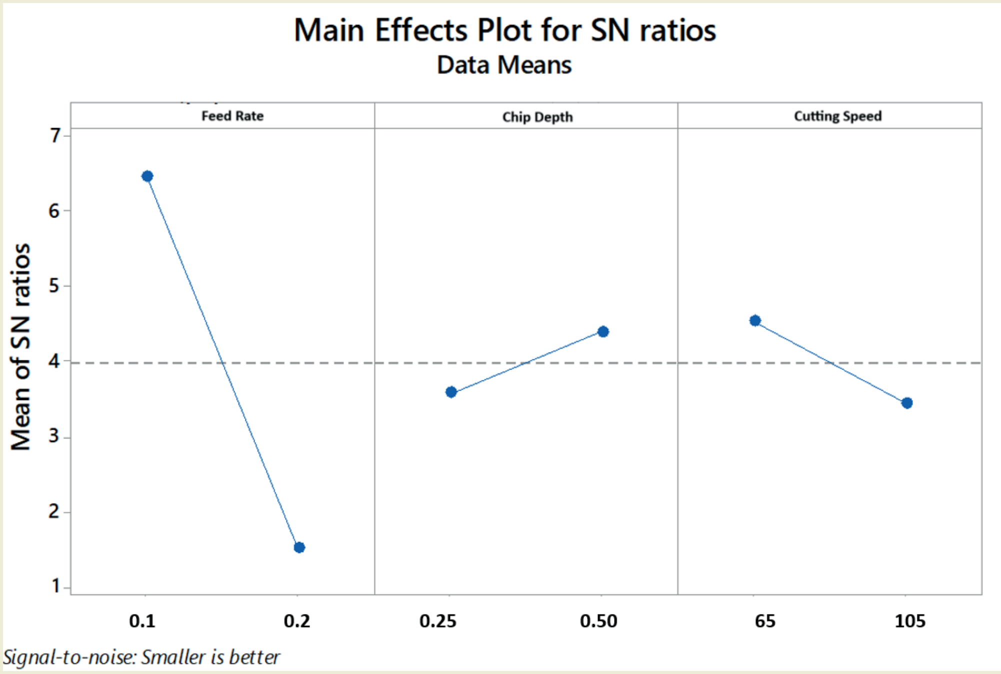

Figure 5. Main effects of S/N ratios for surface roughness – 0.4 corner Radius

not significant (p>0.05). In addition, when the percentage effects of the factors were analyzed: 93.5% for feed, 4.5% for speed and 0.8% for depth of chip. Also, the coefficient of determination (R-Sq(adj)) for the model was found to be 98.00%.

When the ANOVA analysis for 0.4 corner radius was analyzed in ▶**Table 6**, it was seen that the feed rate factor was statistically significant for S/N ratios (p<0.05), but the cutting speed and chip depth factors were not significant (p>0.05). In addition, it was understood that the highest percentage factor effect was the feed rate factor with 89.1% and the coefficient of determination (R-Sq(adj)) for the model was 92.92%. It can be seen that the experimental results have a high accuracy and according to the ANOVA table for both end radius, the feed factor was the most important factor for roughness. This point of view was in accordance with the literature [60-63].

3.2. Evaluation of Cutting Force

Cutting force (N) values obtained from turning experiments with cutting tools coded CCMT 09T308-304 and

CCMT 09T304-304 with machining parameters are given graphically in ▶Figure 6. Looking at the graph, it has been observed that the cutting forces increase with the increase in feed. This could be explained by the effect of the increase in the load on the tool at higher feed rates [64, 65]. It has been understood from the graph that the forces increase with the increase in feed in machines with both different corner radius. However, it could be seen that the lowest force value had occurred at 105 m/min speed, 0.25 mm chip depth and 0.1 mm/rev feed with 0.8 corner radius tool, while the highest cutting force value had occurred at 105 m/min speed, 0.5 mm chip depth and 0.2 mm/rev feed with 0.4 corner radius tool. It has been thought that the reason for this situation was that in machining with a tool with a smaller corner radius, the load was concentrated on a smaller area due to the smaller contact surface of the tool with the workpiece and the cutting forces increased as a result of the increase in feed rate [38, 66]. When the graph was analyzed, it has been seen that the force values increased with the increase in the depth of chip parameter. This can be explained that tool wear occured due to the increase in the tool-workpiece contact time, resulting in a decrease in the performance of the tool. Due to the decreased tool performance, the machine zone has more loaded, resulting in an increase in cutting forces. Studies similar to this situation are available in the literature [67, 68]. It could be understood from the graph that the cutting force values increase with increasing chip depth in both 0.4 and 0.8 corner radius machining. However, it has realized that the lowest value in the cutting force form in the combination of a speed of 105 m/min, a chip depth of 0.25 mm and a feed of 0.1 mm/rev with a 0.8 corner radius tool. This has thought to be due to the fact that the forces were evenly distributed due to the wider contact surface of the tool in machining with higher corner radius [11, 26, 69, 70].

In the graph, when the cutting force results were analyzed according to the cutting speed variation, it has seen that different cutting force values occur at different tool corner radius.

In machining with 0.8 corner radius, the force has decreased as the speed increased, while in machining with 0.4 corner radius, the force has increased as the cutting speed increased. This can be explained that the contact area of the 0.8 corner radius was wider, which results in less friction in the machining area and therefore reduces the cutting forces. However, during machining with 0.4 corner radius, it has been observed that since the contact surface of the tool was narrower, it can applied more friction on the machining surface, causing an increase in cutting forces.[71, 72].

According to the results of the graphical evaluation of turning experiments performed with cutting speed, feed, chip depth and 0.4-0.8 corner radius tool; lower cutting forces were obtained as a result of machining with 0.8 corner radius tool in AA 6082 aluminum material.

The analysis result graphs according to the cutting force has been given in ▶Figure 7 and ▶Figure 8 for tools with 0.8 and 0.4 corner radius, respectively. When the S/N ratios graph for 0.8 corner radius was analyzed in ▶Figure 7, it can be understood that the factor with the largest variation for the cutting force was the chip depth (0.25, 0.5 mm). The chip depth factor has been followed by the feed and speed factors. The least variation has been observed in the cutting speed factor (65, 105 m/min). When the graph of S/N ratios for tools with 0.4 corner radius was analyzed in ▶Figure 8, the biggest variation between the ratios has been seen in the feed factor, while the variation in the speed factor was the lowest. As a result of the analysis for cutting

Table 5. ANOVA table for surface roughness - 0.8 corner radius

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PC (%)
Feed rate	1	52.6205	52.6205	52.6205	327.41	0.000	93.5
Chip depth	1	0.4777	0.4777	0.4777	2.97	0.60	0.8
Cutting speed	1	2.5335	2.5335	2.5335	15.76	0.017	4.5
Residual Error	4	0.6429	0.6429	0.1607			1.2
Total	7	56.2746					100
R-Sq(adj): 98.00%							

Table 6. ANOVA table for surface roughness - 0.4 corner radius

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PC (%)
Feed rate	1	48.739	4.739	48.7393	88.18	0.001	89.1
Chip depth	1	1.357	1.357	1.3568	2.45	0.192	2.5
Cutting speed	1	2.314	2.314	2.3143	4.19	0.110	4.3
Residual Error	4	2.211	2.211	0.5527			4.1
Total	7	54.621					100
R-Sq(adj): 92.92%							

force, ANOVA analysis was performed to see the effect of the factors.

The results of the analysis were given in ▶Table 7 and ▶Table 8 for 0.8 and 0.4 corner radius, respectively. When the ANOVA analysis for 0.8 corner radius has been analyzed in ▶Table 7, it was seen that the chip depth and feed rate factors were statistically significant for S/N ratios ($p<0.05$), but the cutting speed factor was not significant ($p>0.05$). Also, when the percentage effects of the factors were analyzed: 48.5% for depth of cut, 41.7% for feed rate and 1.5% for cutting speed. Also, the coefficient of determination (R-Sq(adj)) for the model was found to be 85.51%.

When ANOVA analysis for 0.4 corner radius has been analyzed in ▶Table 8, it was seen that feed and chip depth factors were statistically significant for S/N ratios ($p<0.05$), while cutting speed factor was not significant ($p>0.05$). It was also understood that the highest percentage factor effect was the feed rate factor with 54.9% and the coefficient of determination (R-Sq(adj)) for the model was 76.92%. When ANOVA results were analyzed according to the cutting force, it was observed that the most important factor for 0.8 corner radius was the chip depth, while for 0.4 corner radius it was the feed rate factor. In the results of the analysis, it was thought that in machining with a cutting tool with a corner radius of 0.8 mm, due to the large contact surface, it caused the tool to contact with more material during the chip removal process, and in this case, chip depth has stand out as the most important factor for cutting forces [36,

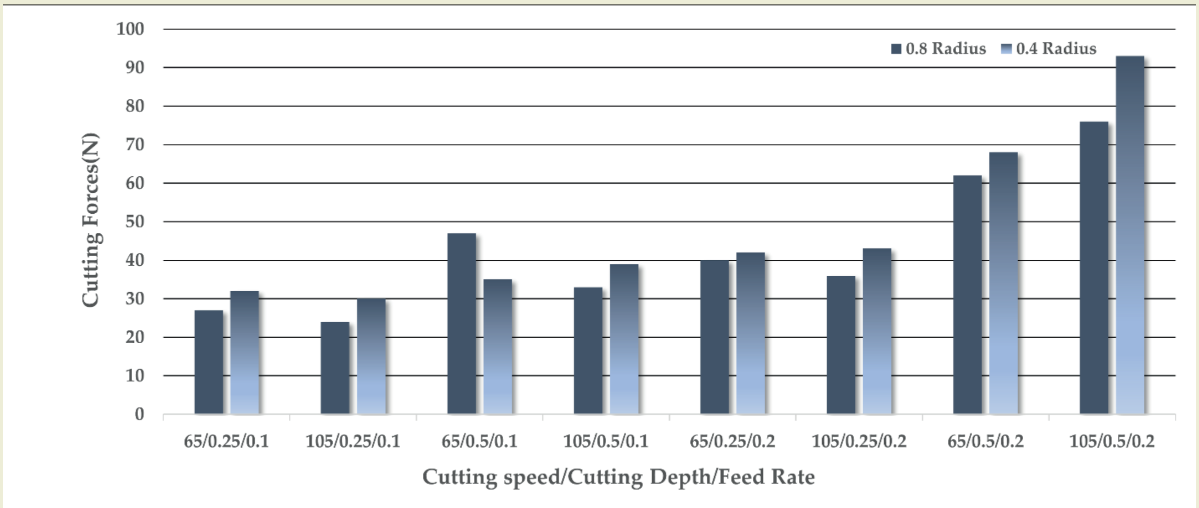

Figure 6. Cutting Force variation vs. cutting speed, chip depth and feed rate

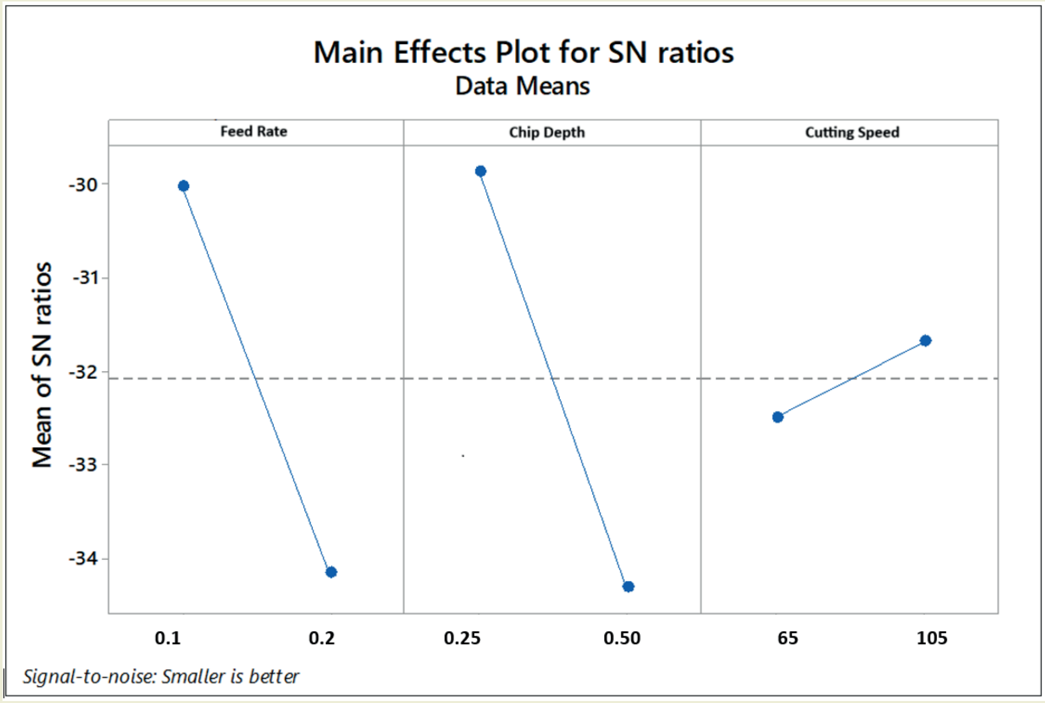

Figure 7. Main effects of S/N ratios for cutting force – 0.8 corner radius

https://doi.org/10.26701/ems.1666294

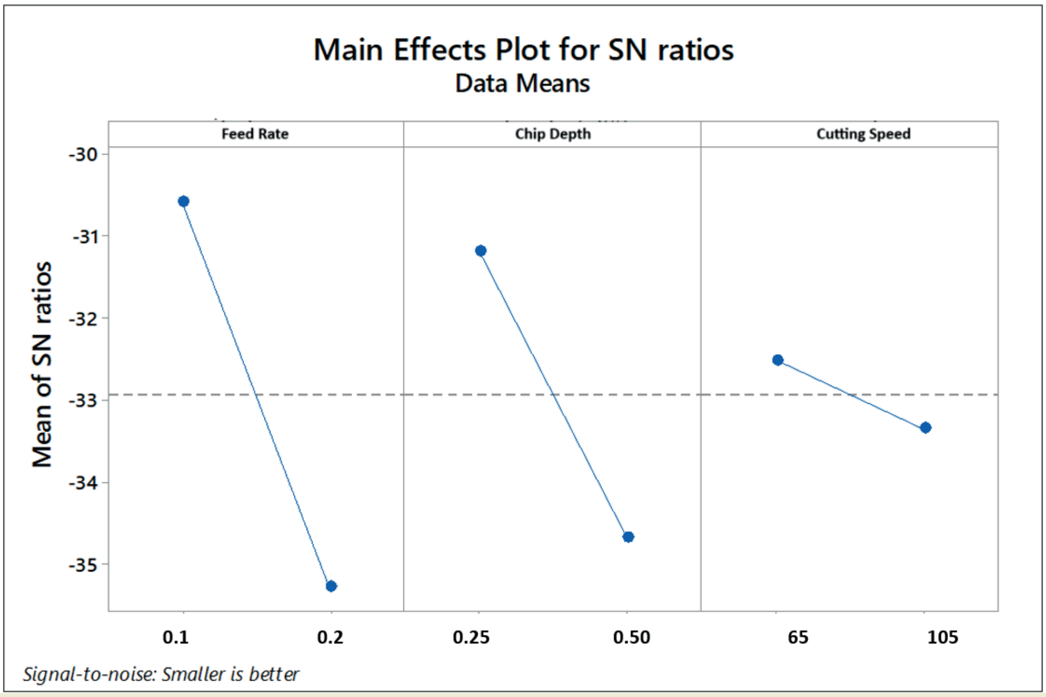

Figure 8. Main effects of S/N ratios for cutting force – 0.4 corner radius

Table 7. ANOVA table for cutting force - 0.8 corner radius

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PC (%)
Feed rate	1	34.394	34.394	34.394	20.14	0.011	41.7
Chip depth	1	39.951	39.951	39.951	23.39	0.008	48.5
Cutting speed	1	1.313	1.313	1.313	0.77	0.430	1.5
Residual Error	4	6.832	6.832	1.708			8.3
Total	7	82.490					100
R-Sq(adj): 85.51%							

Table 8. ANOVA table for cutting force - 0.8 corner radius

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PC (%)
Feed rate	1	44,209	44,209	44,209	16,66	0,015	54.9
Chip depth	1	24,300	24,300	24,300	9,16	0,039	30.2
Cutting speed	1	1,364	1,364	1,364	0,51	0,513	1.7
Residual Error	4	10,614	10,614	2,653			13.2
Total	7	80,486					100
R-Sq(adj): 76.92%							

73, 74]. In machining with a 0.4 mm corner radius tool, it was observed that changes in feed rate become more dominant in force values, since the contact area of the tool was reduced [32, 75, 76].

4. Conclusions

The important findings obtained in the study carried out to investigate the cutting forces and surface roughness depending on the machining parameters in the AA 6082 aluminum alloy on a conventional lathe with tools with two different radius are summarized below:

- 0.8 and 0.4 corner radius cutting tools, the results of machining with 0.8 corner radius cutting tool showed better results than machining with 0.4 corner radius cutting tool in terms of both roughness and force values.

- According to the graphical evaluation results, the highest surface roughness value was observed at 105 m/min cutting speed, 0.5 mm chip depth and

0.2 mm/rev feed rate with 0.4 corner radius tool, while the lowest surface roughness value occurred at 65 m/min cutting speed, 0.5 mm chip depth and 0.1 mm/rev feed rate with 0.8 corner radius tool.

- According to the results of the graphical evaluation for cutting forces, the highest cutting force value was observed at 105 m/min cutting speed, 0.5 mm chip depth and 0.2 mm/rev feed rate with 0.4 corner radius tool, while the lowest cutting force value occurred at 65 m/min cutting speed, 0.25 mm chip depth and 0.1 mm/rev feed rate with 0.8 corner radius tool.
- The best roughness results were obtained with tools with 0.8 corner radius and the worst roughness results were obtained with tools with 0.4 corner radius. For both cutting tools, the roughness increased with an increasing feed.
- In the experiments with 0.8 and 0.4 corner radius cutting tools, roughness decreased with an increasing chip depth. However, when the speed was 105 m/min and the feed was 0.2 mm and the chip depth increased from 0.25 to 0.5 for the tool with 0.4 corner radius, the surface roughness values did not decrease and even increased slightly contrary to this general behavior.
- For all cutting tools, surface roughness increased with increasing speed. It was evaluated that the selected speed values in the roughness values were low to provide the expected improvement.
- ANOVA analysis revealed that the feed and speed factors should be taken into consideration primarily for both cutting tools in reducing the surface roughness in turning AA 6082 aluminum alloy.
- The lowest S/N ratios obtained as a result of analysis (smaller is better) in obtaining the lowest surface roughness were determined by the factors and levels of feed (0.2 mm / rpm), chip depth (0.5 mm) and speed (105 m / min) for both different tools.
- In terms of cutting force, the tool with 0.8 corner radius showed the best performance, while the worst performance was obtained with the tool with 0.4 corner radius. For both cutting tools, the cutting forces increased continuously with increasing feed rate and chip depth.
- With increasing the speed, the cutting forces decreased for the tool with 0.8 corner radius. The same was not observed for machining with a tool with a 0.4 corner radius, on the contrary, the forces increased.
- According to the results of ANOVA analysis in reducing the cutting force in turning AA 6082 aluminum alloy, it was found that for the tool with 0.8 corner radius, the factors of chip depth and feed rate should be considered first, while for the tool with 0.4 corner radius, the factor of feed rate should be considered first and then chip depth.
- The lowest S/N ratios obtained as a result of analysis (smaller is better) in obtaining the lowest cutting force were determined at the factors and levels of feed (0.2 mm/rev), chip depth (0.5 mm) and speed (65 m/min) for the tool with 0.8 corner radius. For the tool with 0.4 corner radius, the factors and levels of feed (0.2 mm/rev), chip depth (0.5 mm) and speed (105 m/min) were determined.
- In addition to the cutting tool geometry, additional factors such as the approach angle of the tool to the machined material and whether it is coated or not have an effect on surface roughness. However, although these aspects were not evaluated in this study, it is foreseen that they will provide opportunities for future research. More extensive studies can be carried out in which the effects of more variables on more cutting parameters/levels can be interactively evaluated and optimized.
- This study systematically investigated the influence of tool corner radius and machining parameters on the machinability of AA6082 aluminum alloy and provided original experimental data to the literature. The findings on the inter-correlation between cutting forces and surface roughness can provide a solid basis for future modeling and optimization studies. Through an industrial point of view, it has become possible to increase production efficiency by determining the optimum tool corner radius and machining conditions. In this context, the study can be an important reference for both academic research and practical production processes.

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Research ethics

Not applicable.

Author contributions

Conceptualization: [Ayşe Sena Yamaner, Bahar Sayın Kul], Methodology: [Ayşe Sena Yamaner], Formal Analysis: [Ayşe Sena Yamaner, Bahar Sayın Kul], Investigation: [Ayşe Sena Yamaner, Bahar Sayın Kul], Resources: [Ayşe Sena Yamaner, Bahar Sayın Kul], Data Curation: [Ayşe Sena Yamaner, Bahar Sayın Kul], Writing – Original Draft Preparation: [Ayşe Sena Yamaner, Bahar Sayın Kul], Writing - Review & Editing: [Bahar Sayın Kul], Visualization: [Ayşe Sena Yamaner], Supervision: [Bahar Sayın Kul], Project Administration: [Bahar Sayın Kul], Funding Acquisition: [Bahar Sayın Kul]

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Data availability

The raw data can be obtained on request from the corresponding author.

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