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Statistical and experimental analysis of machining parameters and tool radius in turning of low carbon steels

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Abstract – In this study, the effects of basic machining parameters and insert radius on machinability during turning of low-carbon steels were investigated using experimental and statistical methods. The experiments were conducted on AISI 1015 case-hardened steel, and speed, depth, feed, and insert radius were considered as input parameters. Output parameters were determined as roughness and cutting force. The full factorial method was used for the experimental design, and the obtained data were evaluated using ANOVA. The results show that feed and insert radius are particularly decisive on roughness. At low feed and high cutting speed, a 0.8 mm insert radius provides optimum surface quality. Cutting force increases in direct proportion to depth of cut and feed, while decreasing with increasing speed. It was also observed that tools with a 0.4 mm insert radius exhibit lower force values. According to the ANOVA results, feed was the parameter that most affected surface roughness at a 0.4 mm tip radius, while depth was the most critical parameter determining force at a 0.8 mm tip radius. Consequently, this study provides guidance in selecting optimal cutting parameters to achieve high efficiency and desired tolerances in manufacturing processes.

Keywords – ANOVA, 1015, Cutting Force, Surface Roughness, Machinability.

I. INTRODUCTION

Low carbon AISI 1015 steel is widely used as lever arm, bushing, roller, spool, gear wheel, measuring instrument and similar structure and machine parts. Some of the main reasons for its use in this field are weldability due to its low carbon properties and very good bending strength. What makes this steel really important is that it is an alloy used in many areas with its versatile machinability such as hot rolled, normalised and cold working. On the other hand, due to its low carbon levels, accessibility to the material is easy and it has become an attractive option because it is relatively cheaper than other steels [1-3].

Today the developing technology also provides development in the field of manufacturing. Apart from technology, increasing competition has made it necessary to make the production in the best way. However, although the technology is advanced, some of the tolerances required by the customer can be met with manufacturing methods [4-7]. In order to obtain products with the tolerances required by the customers, we need to apply machinability studies in manufacturing methods. Traditional manufacturing methods are optimised with technology and the desired tolerances can be achieved with machinability studies. Among the traditional manufacturing methods, the most common method used when processing products is machining methods [8-10]. Turning, milling, threading and drilling are examples of machining methods.

Turning method is the most widely used method among machining methods [11-16]. The reason for this is that turning is a more economical method than other methods. Turning is the process of chip removal in the work axis of the cutting tool at each rotation of the workpiece. In order to machine a product with the desired tolerances on the lathe, we must know the tool and parameters suitable for the material. In this study, a tool with CCMT geometry with Titanium Carbide (TiC) coating is used as cutting tool. Titanium Carbide (TiC) coating on the cutting tool increases the wear resistance of the cutting tool, strengthens its resistance to high temperatures and extends the life of the tools. This coating also increases the hardness of the tool, enabling more efficient cutting operations. At the same time, the CCMT geometry defines the multi-tooth structure at the tip of the cutting tool. This geometry helps to obtain a smoother and faster surface in the course of the cutting process. Such geometries increase the durability of the cutting tool, while providing less heating of the workpiece and cutting with less vibration.

There are many researches for carbon steels in the literature. A summary of these researches is given below. Kavak and Üstel investigated the machinability of 1040 material by turning method. In their study, they focused the effects of speed, chip depth, feed on roughness with uncoated cemented carbide cutting tool in dry environment. They observed that the surface roughness value is inversely proportional to the cutting speed and directly proportional to the feed rate. They observed that the worst surface roughness value was observed in the experiment with tubular tangle type chips, while the best roughness value was observed with strip chips [17]. Binali et al. investigated the machinability of S960QL structural steel by finite element method. They investigated the effect of lateral depth, axial depth, speed and feed as cutting parameters on cutting force, moment value and temperature. In general, it was stated that an increase in the amount of feed and depth of cut resulted in an increase in cutting forces, moments and temperatures. They stated that the lowest moment value and temperature value occurred at the parameters where the cutting force was the lowest. As a result, it was concluded that machining parameters can be used for the prediction of machinability outputs in milling process by finite element method [18]. Ali et al. investigated the machinability of 1020 steel by milling method. In their study, they compare wet machining with conventional wet machining. While speed, feed, depth were the input parameters in both experiments, surface roughness and hardness were determined as output parameters. As a result, they found that wet machining produced lower surface roughness and higher hardness than wet machining. However, they found that the feed rate is most important in the case of roughness in wet machining and spindle rotation in wet machining. They concluded that the best parameters in the two methods are the same for minimising roughness, but different for maximising hardness [19]. Shnfir et al. studied the efficiency of ceramic tools in milling AISI hardened 1045 steel. In their study, they aimed to determine the effects of cutting parameters, milling configuration, edge preparation and work material hardness on machinability values such as cutting force, power consumption and side tool wear. As a result, they found that the most important factor affecting the compound force was feed rate. The factors affecting the cutting power were cutting speed and feed rate. In contrast to other factors, tool selection and milling kinematics had a greater effect on tool wear [20]. Salman et al. investigated the machinability of AISI 1035 alloy by dry turning method. In their study, speed, feed, depth as well as the nose radius of the cutting tool and coating condition were added to the parameters. They investigated the surface residual stresses generated during machining of AISI 1035 alloy with the cutting parameters given in the study. As a result, uncoated cutting tool, small nose radius and low cutting speed and reduction of feed rate decreased the generated temperature and also less surface pulling force was encountered [21]. Kumar et al. investigated the optimisation of surface roughness and material removal rate of AISI 1005 steel by using Taguchi method in milling method. As a result of their research, they stated that depth and feed are the most effective parameters for roughness and material removal rate, respectively [22]. Paul et al. compared the role of cryogenic cooling in tool wear and surface quality of AISI 1060 steel by turning method and the effectiveness of cryogenic cooling with dry and oily environments. In their research, they observed that the most tool wear and roughness occurred in dry machining. They stated that machining of AISI 1060 steel with cryogenic cooling results in less tool wear, better tool life and surface quality compared to other environments [23]. In their research, Binali et al. aimed to investigate the effects of cutting parameters in MQL and dry cutting environments on the turning properties of S235JR low carbon steel to create a sustainable cutting. As a result, the most suitable range for S235JR steel is lower machining parameters and MQL environment. [24]. There is no research on cutting tool nose radius and machine learning in the literature.

In this study experiments were carried out to observe the results of the basic parameters defining the machining process. Depending on the cutting tool used in the machining of AISI 1015 cementation steel, the effects of input and output parameters were monitored and based on these effects, the optimum compatibility between the parameters was determined. This determination is of great importance especially in achieving high productivity and desired tolerances in production processes. Cutting speed, chip depth, feed, cutting tool nose radius, cutting force and roughness values were considered as input parameters and cutting force and roughness values were considered as output parameters. Experimental design technique was used to interpret the relationship between these parameters. For the experimental design, the full factorial design method was used. Two experiments for each of the input parameters and eight experiments in total were evaluated using full factorial design. In the study, ANOVA was used to evaluate the effects of the input parameters on each other for the values between cutting parameters and roughness.

II. MATERIALS AND METHOD

In this research, low carbon AISI 1015 steel, which is known to be used in many manufacturing sectors, was selected. The test material is a workpiece with a diameter of 65 mm and a machining length of 200 mm. Table 1 indicates the chemical content of the steel used in the research. Speed, depth and feed were determined by full factorial approach. Using a full factorial approach as an experimental design to evaluate and interpret the effects of factors is considered to be the most ideal approach as all combinations of various factors at different levels are evaluated. As a result, a total of 16 experiments were carried out in this experiment. In the first stage of the experimental design, cut-off values that could affect the output values were selected. All factors were selected in accordance with the characteristics of this research and the selected factors were selected at two levels. After the variables and levels were selected, all combinations of these levels were organised by experimental design. In the next stage, four factors were tested at the same time with experiments and the results were evaluated with Anova. Table 2 shows the factors used in the experiments and their levels.

Table 1. Chemical content of AISI 1015 [25].

Elements	Content
C %	0.138
Mn %	0.392
P %	0.014
S %	0.024
Cr %	0.221
Cu%	0.232
Fe %	Bal.

The cutting tool was selected based on practical applications and manufacturer's recommendations. KORLOY CCMT 09T308 and CCMT 09T304 series were selected as cutting tools. The workpiece and experimental design are given in Figure 1.

Table 2. Turning test levels

Cutting parameters	Level 1	Level 2
Speed (mm/min)	60	80
Depth (mm)	0.2	0.4
Feed(mm/rev)	0.2	0.4
Cutting tool nose radius	0.8	0.4

The experimental setup was installed on a S547-8899 DE LORENZO lathe. During the experiments, a dynamometer was used to measure the force and a portable pertometer was used to measure the roughness. The average roughness value was determined with 20 mm roughness measurement repetition at a machining length of 200 mm.

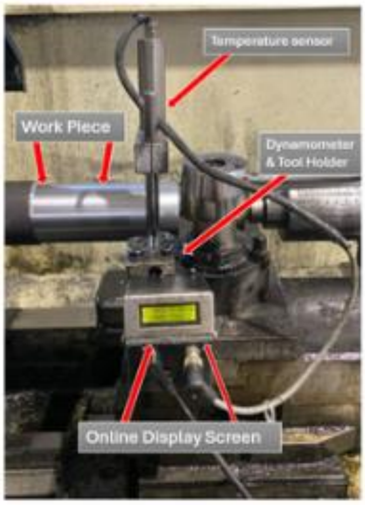

Figure 1. Experiment Design

III. RESULTS

To evaluate and determine the effects of input and output parameters on the cutting process requires an in-depth analysis of the parameters. Table 3 shows the experimental results. The values obtained are evaluated using ANOVA analysis.

Table 3. Experimental results

Feed	Depth	Speed	Ra_0.8	Ra_0.4	F_0.8	F_0.4
0.2	0.2	60	0.581	0.683	211.3	102.8
0.2	0.2	80	0.537	0.569	113.1	95.2
0.2	0.4	60	0.635	0.745	287.9	231.1
0.2	0.4	80	0.449	0.611	268.7	220.3
0.4	0.2	60	0.947	1.139	251.1	244.4
0.4	0.2	80	0.854	1.106	218.3	192.3
0.4	0.4	60	0.958	1.060	454.7	377.8
0.4	0.4	80	0.973	1.395	286.1	204.5

A. *Surface Roughness Analysis*

As shown in Figure 2, roughness is of great importance in manufacturing stages as it affects the properties and quality of the main product. It has a direct effect on the working performance of the main product. This is because the manufactured parts are constantly in contact with each other to form a whole in real life. The tribological effects that the collaborating parts exert on the contact surfaces determine the service life of the material and this directly affects the cost of the machine. Therefore, determining the surface quality of the material is of great importance as it facilitates the manufacturing process and reduces the cost in the long term. The machining parameters, heat treatment and cutting environment and the difficulty of chip removal have a significant effect on the surface quality. Clearly, the nose radius and feed are among the important factors for surface roughness. Low feed rate decreases the roughness value at both nose radius. The average Ra roughness value obtained varies between 0.449-1.395 µm. Optimum roughness was observed at the level where low feed, high chip depth and high speed values were applied with 0.8 mm nose radius. It is also observed that 0.8 mm nose radius provides a better roughness value than 0.4 mm.

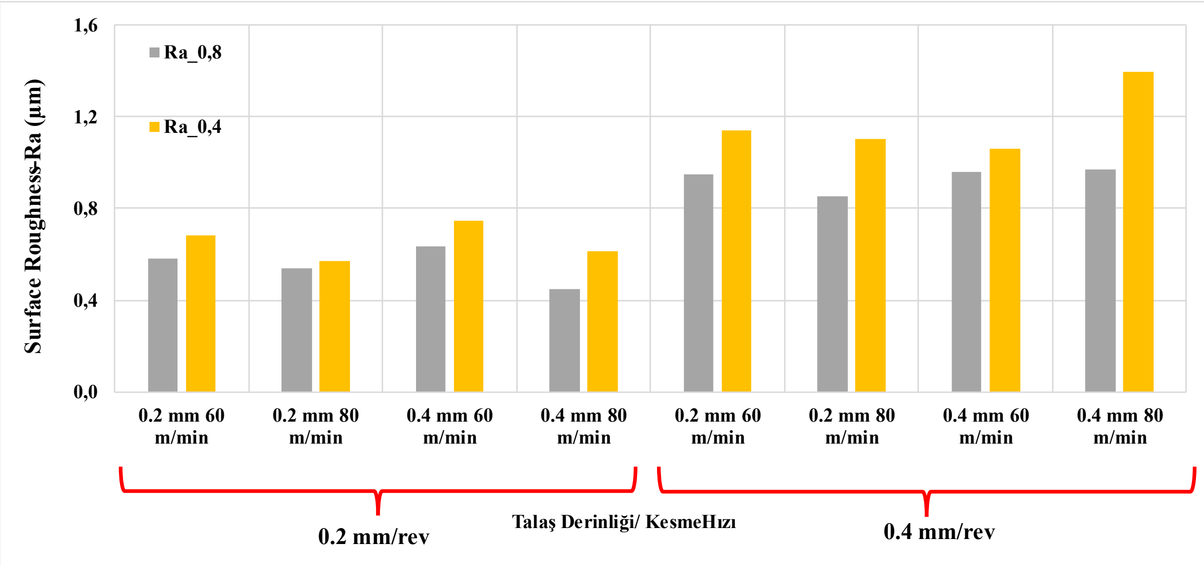

Figure 2. Surface Roughness Values

B. *Cutting Force Analysis*

Force is one of the most important forces that occurs between the workpiece and the insert during chip removal and provides chip removal from the material. The reason why cutting force is so important is that it directly affects tool life and surface quality. High cutting forces can affect the stability of the machine and cause vibration in the machine. This vibration can damage both the tool and the workpiece and make it difficult to obtain a product with the desired tolerances. High cutting forces can also increase energy consumption. Unexpected force changes can cause the tool to break and the workpiece to eject, which is an important situation in terms of occupational safety. For these reasons, it is necessary to keep the cutting force at certain levels. As shown in Figure 3, the relationship between speed and chip depth and cutting tool nose radius significantly affects the cutting force. While the average cutting force obtained was between 113.1-454.7 N for the tool with a radius of 0.8, it decreased to 95.2-377.8 N for the tool with a radius of 0.4. The smallest cutting force was observed at values where the feed and chip depth were low and the cutting speed was high. The largest force was observed at high feed and chip depth values and low cutting speed values. It was observed that the cutting force decreased as the cutting speed increased at both nose radii. As the chip depth and feed increased, the force also increased. The observed results are in accordance with the literature. The optimum force was obtained with a cutting tool with a nose radius of 0.4 at low feed, low chip depth and high speed. The difference between the smallest measured value and the largest value is approximately 4.77 times, which is a significant change.

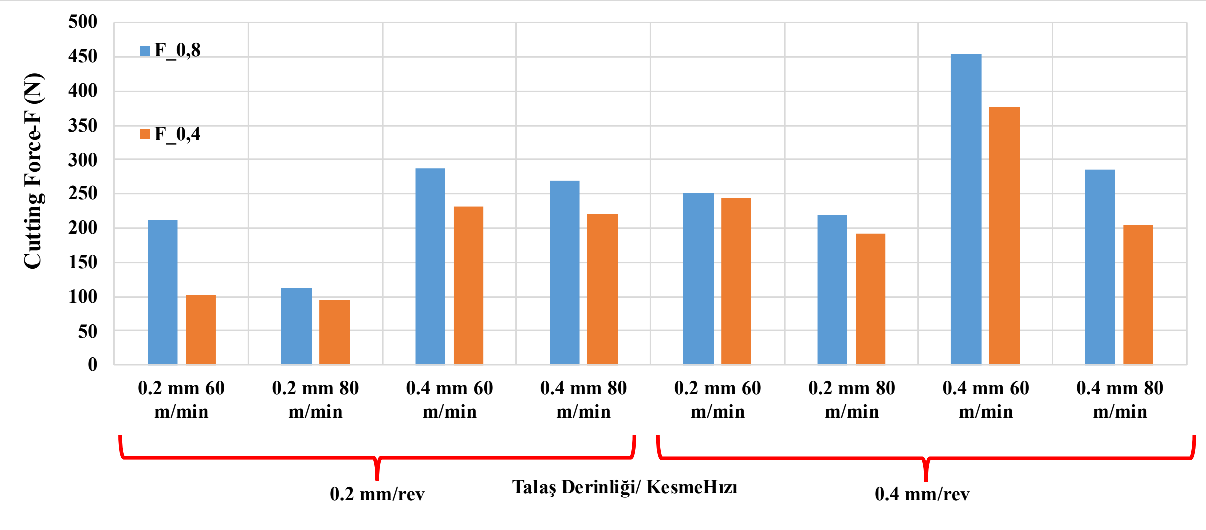

Figure 3. Cutting Force Values

C. *Statistical ANOVA Evaluation*

A statistical method known as analysis of variance was used to study the effects of feed, tool nose radius and speed on roughness and force.

D. *Statistical Analysis for Surface Roughness*

When Table 4 and 5 is analysed, it is seen that the primary factor affecting the surface roughness at 0.8 nose radius is feed rate. Delta factor value ranks first with 4.6415, followed by speed with 1.1169. The R^2 value of 93.47% provides a high reliability. Feed is the main factor determining the roughness with respect to the nose radius of 0.8.

Table 4. Statistical effect of parameters on surface roughness for 0.8 nose radius

Level	Feed	Depth	Speed
1	5.2556	2.9904	2.3764
2	0.6141	2.8793	3.4933
Delta	4.6415	0.1110	1.1169
Rank	1	3	2

Table 5. ANOVA analysis for 0.8 nose radius

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed Rate	1	43.0863	43.0863	43.0863	54.07	0.002
Depth of Cut	1	0.0247	0.0247	0.0247	0.03	0.869
Cutting Speed	1	2.4951	2.4951	2.4951	3.13	0.152
Residual Error	4	3.1872	3.1872	0.7968		
Total	7	48.7933				
R^2= 93.47%						

Table 6 and 7 shows the results obtained by the ANOVA method on the effect of process parameters on the roughness of the tool with 0.4 nose radius. According to the results, it is seen that the primary factor of 0,8 nose radius is the feed rate with a delta value of 5,1119. In terms of variance, the secondary important factor is the chip depth with a value of 0,6940. The reliability of the analysed model presents a high reliability with an R^2 value of 90.75%.

Table 6. ANOVA analysis for 0.4 nose radius

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed Rate	1	52.2636	52.2636	52.2636	38.42	0.003
Depth of Cut	1	0.9632	0.9632	0.9632	0.71	0.447
Cutting Speed	1	0.1750	0.1750	0.1750	0.13	0.738
Residual Error	4	5.4415	5.4415	1.3604		
Total	7	58.8433				
R2= 90.75%						

Table 7. Statistical effect of parameters on surface roughness for 0.4 nose radius

Level	Feed Rate	Depth of Cut	Cutting Speed
1	3.7615	1.5525	1.0576
2	-1.3505	0.8585	1.3534
Delta	5.1119	0.6940	0.2958
Rank	1	2	3

E. *Statistical Analysis for Cutting Force*

Table 8 and 9 presents the results of the statistical analyses performed to determine the most important factors affecting the cutting force for a nose radius of 0.8. According to the results, the most important factor affecting the cutting force is chip depth with a delta value of 4.43. Following this, feed rate is the second most important factor with a value of 2.93. According to the adjusted coefficient of the model, a model with a high reliability of 89.16% was created.

Table 8. Statistical analysis of parameters on cutting force for 0.8 nose radius

Level	Feed Rate	Depth of Cut	Cutting Speed
1	-46.33	-45.59	-49.21
2	-49.27	-50.01	-46.39
Delta	2.93	4.43	2.82
Rank	2	1	3

Table 9. ANOVA analysis for 0.8 nose radius

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed Rate	1	17.186	17.186	17.186	7.82	0.049
Depth of Cut	1	39.205	39.205	39.205	17.84	0.013
Cutting Speed	1	15.872	15.872	15.872	7.22	0.055
Residual Error	4	8.788	8.788	2.197		
Total	7	81.050				
R2= 89.16%						

Table 10 and 11 shows the results of the statistical analyses of the experiments performed with 0.4 nose radius. In the light of the findings obtained, it is seen that the data are similar to the data of 0.8 nose radius. The most important factor was the chip depth with a value of 4.66. This is followed by the feed rate with a value of 4.31. The reliability level of the model, according to the R^2 value of 81.62%, is a moderately acceptable model; however, it can be concluded that it is open to improvement.

Tablo 10. Statistical analysis of parameters on cutting force for 0.4 nose Radius

Level	Feed Rate	Depth of Cut	Cutting Speed
1	-43.49	-43.31	-46.71
2	-47.80	-47.97	-44.58
Delta	4.31	4.66	2.12
Rank	2	1	3

Tablo 11. ANOVA analysis for 0.4 nose radius

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed Rate	1	37.210	37.210	37.210	7.37	0.053
Depth of Cut	1	43.430	43.430	43.430	8.61	0.043
Cutting Speed	1	9.021	9.021	9.021	1.79	0.252
Residual Error	4	20.184	20.184	5.046		
Total	7	109.844				
R2= 81.62%						

IV. CONCLUSION

This paper aims to determine the optimum compatibility between machinability input parameters and output parameters depending on the material and cutting tool and to determine the optimum machining parameters. A series of experiments were carried out to investigate sustainable cutting conditions with 0.4- and 0.8-mm nose radius tools to achieve the following characteristics. Surface quality and cutting force were evaluated as output parameters. The obtained output parameters were analysed by statistical analyses and graphical plots.

- Among the machining parameters, especially feed and radius are the determining factors on surface roughness. 0.8 mm nose radius provides optimum surface quality with low feed and high speed.
- It is observed that the cutting force increases in direct proportion to the feed rate and chip depth and decreases with the increase in speed. In addition, it was found that the cutting tool with 0.4 mm nose radius provides lower cutting force values.
- When the ANOVA data are analysed, it is seen that the parameter that most affects the surface roughness of the cutting tool with 0.4 mm nose radius is the feed.
- When the ANOVA data are analysed, it is seen that the most critical parameter determining the cutting force at 0.8 mm radius is the depth, followed by the feed and the obtained model offers high reliability.

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