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Research Article

Investigation of the Effects of Cutting Fluid Application with Minimum Quantity Lubrication (MQL) Method on the Machinability of Pure Titanium

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ABSTRACT

Machining is one of the widely used methods in today's technology and there are many parameters that affect the machinability of the produced product. In the machining process, the machinability of the product depends on parameters such as feed rate, depth of cut, cutting speed and cutting fluid. The use of cutting fluid during the process has advantages such as improving surface quality, but also disadvantages such as increased cost and environmental damage. Due to these disadvantages of cutting fluid in manufacturing processes, alternative methods have been developed. The method called minimum quantity lubrication (MQL) not only reduces cost but also improves machinability. In this study, the machinability of titanium turning was evaluated with main cutting force, surface roughness and temperature measured in the primary cutting zone data. MQL method was used in the study and Taguchi L9 model was applied. The results were compared between dry cutting and MQL atmospheres. The reliability of the data and the degree of influence of the parameters were analyzed by ANOVA. In this study, the shear force data obtained in the dry shear atmosphere were higher than the data obtained in the MQL method. In addition, the surface roughness values obtained in dry cutting atmosphere were also relatively high. The optimum cutting speed, feed rate and depth of cut values for the process were determined as 60 m/min, 0.05 mm/rev and 0.5 mm, respectively.

1. Introduction

In the manufacturing industry, technology is developing day by day to a degree that is difficult to follow. The manufacturing method to be chosen for the production of the object to be manufactured is decided by considering its advantages and disadvantages. Machining process is one of the most preferred methods in the manufacturing sector due to its advantages as well as its disadvantages such as the formation of residual parts we call chips and high temperature. To remove heat generated during the machining process, The Minimum Quantity Lubrication (MQL) method is the application of the minimum amount of cutting fluid to the cutting zone with sustainability in mind, is becoming widespread day by day. In this method, the cutting fluid is sprayed through a nozzle tip and applied to the cutting zone. By aiming to minimize the consumption of cutting fluid, the MQL method prioritizes environmental sensitivity and reduces costs. With all these advantages, MQL method improves machinability. Studies using the MQL technique have generally investigated the effect of cutting atmosphere on machinability.

The MQL technique has been used in machining processes such as drilling [1], turning [2, 3], milling [4, 5]. In the studies, the effect of machining cutting atmosphere has been investigated by considering factors such as

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machinability properties of the materials, tool wear [6, 7], surface roughness [8], cutting temperature [9], cutting oil [10]. In addition, the effect of cutting atmosphere on energy consumption, carbon emission [11], chip morphology [12] has also been studied. In addition, in another study, a region was named as a shadow zone in the MQL technique and the characteristics of the manufacturing process performed in this region were investigated [13]. In addition to the experimental studies, there are also review articles in which current studies are reviewed and future trends are given [14]. Studies using the MQL technique have achieved relatively better results than studies in dry cutting atmosphere [15].

It has been determined that there are studies in the literature using the MQL system and that it is still a subject worthy of further study. The studies were mostly completed using alloyed metallic materials. Since the MQL system is current in the literature and pure metallic materials are used relatively less, this study investigated the processability of pure titanium with the MQL system. The reason why the study was carried out with pure titanium is that titanium is used especially in machining production areas such as ships and submarines, and the coolant we use does not react with pure titanium.

2. Material Method

The study was carried out on a Goodway GLS-150 computer aided (CNC) lathe. Pure titanium material was used in the study and Kistler 9257b dynamometer, FLIR I50 termal camera, Mitutoyo SJ-201 surface roughness measuring device, Werte Mikro STN 15 potentiometer controlled pulvarized lubrication system and Trim E950 cutting fluid were used for the MQL system. The appearance of the system in which the study was carried out is given schematically in Figure 1.

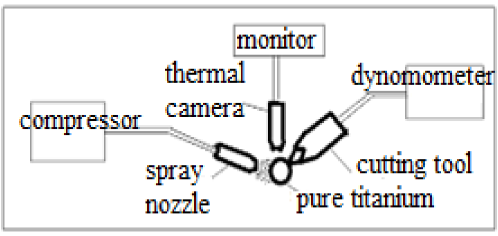

Figure 1. Schematic view of production

Technical specifications of pure titanium used in the study are given in Table 1.

Table 1. Technical properties of pure titanium

Density (g/cm^3)	4.51
Melting point (°C)	1668
Thermal conductivity (W/mK)	21.4
Modulus of elasticity (GPa)	105
Poisson's ratio	0.34
Hardness (BHN)	120

In the study, an MQL system with 0.1 s lubrication interval and 0.1 s lubrication time and bar pressure was used. Trim E950 cutting fluid was used in the study because it is relatively environmentally friendly vegetable-based and has a flash temperature above 160°C. In addition to these features, Trim E950 cutting fluid has a pH value of 8.8 - 9.4 and a refractometer coefficient of 1.0. In the study, Sandvik CNMG 12 04 08-SM 1105 grade PVD TiAlN coated insert and DCLNR 2020K 12 coded lathe tool holder were used.

Three three different depths of cut, three different feeds and three different cutting speeds were used in the study. The selected machining variables are cutting speed 60, 90, 120 m/min, feed 0.05, 0.15, 0.25 mm/rev and depths of cut 0.5, 1, 1.5 mm as given in Table 2. Since 27 experiments will be performed for each machining method in total, Taguchi method orthagonal array was used in order to save both cost and time. Using this method, 9 experiments were performed instead of 27 experiments. The least best approximation was used to evaluate results of the temperature, surface roughness and cutting force.

Table 2. Processing parameters

Parameters	Levels		
Level	Level 1	Level 2	Level 3
Cutting speed (m/min)	60	90	120
Feed rate (mm/rev)	0.05	0.15	0.25
Depth of cut (mm)	0.5	1	1.5

Since we will apply 3 levels and 3 factors in Taguchi method, L9 array was used. The factors and levels of this array are given in Table 3.

Table 3. Factors and levels of experiment numbers

No.	Factors and levels		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3. Results and Discussion

In this study, in order to investigate the effect of machining parameters and cutting atmosphere on the machinability of pure titanium material in the machining process, two different cutting environments, dry cutting environment and MQL method, were realized by applying vegetable-based cutting fluid to the cutting zone. The results obtained were compared in terms of cutting force, temperature measured during the process and surface roughness measured after the process. For each result, the optimal machining parameters were determined according to the signal-to-noise ratios of the results by applying the least-best approach and the effect of processing parameters on the results was determined by analysis of variance.

3.1. Cutting force

The cutting force values obtained in different cutting environments are given in Table 4. The results can be followed visually in Figure 2, which was created with the data in Table 4. As can be seen from Table 4, the effect of the cutting atmosphere was affected by the process parameter values.

Table 4. Cutting force values and percentage of difference

No.	*DRY (N)*	*MQL (N)*	*Difference (%)*
1	134	88	34,33
2	423	326	22,93
3	875	835	4,57
4	451	158	64,97
5	820	450	45,12
6	310	252	18,71
7	575	536	6,78
8	248	183	26,21
9	560	511	8,75

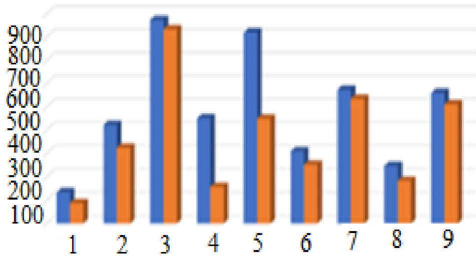

Figure 2. Cutting force values (blue: dry, orange: MQL)

The average of the cutting force values obtained in dry cutting atmosphere is 488 N and 371 N in conditions where cutting fluid is used. Considering the resulting cutting force data, the cutting forces are higher in dry cutting atmosphere.

Minitab application was used to examine the effect of processing parameters. Minitab application was used separately for each atmosphere condition. Signal-to-noise ratio was obtained through Minitab application and the most appropriate machining values were obtained. The Signal to Noise ratio graph obtained for shear force under dry cutting and cutting fluid conditions is given in Figure 3 and the ratio table is given in Table 5.

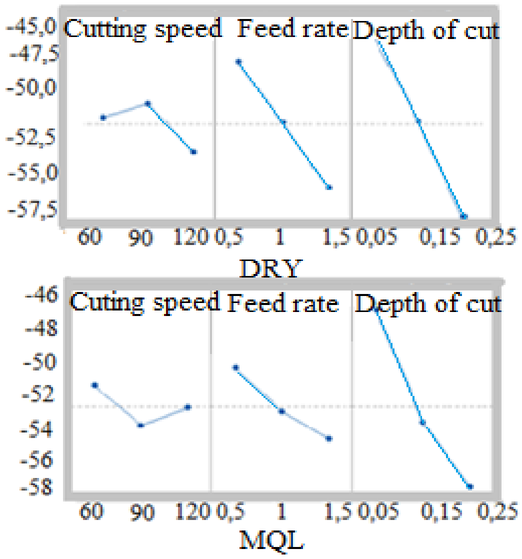

Figure 3. Signal to noise ratio plot of cutting force values for dry cutting and cutting fluid conditions

Table 5. Signal to noise ratio values of cutting force in dry cutting and cutting fluid conditions

No.	Cutting speed (%)	Feed rate	Depth of cut
	DRY		
1	-49,20	-45,82	-44,06
2	-48,36	-49,53	-49,47
3	-51,33	-53,54	-55,36
	MQL		
1	-51,30	-20,27	-46,75
2	-53,73	-52,90	-53,52
3	-52,68	-54,54	-57,44

Signal to Noise Ratio values in dry machining experiments were defined by selecting the smallest best option when performing Taguchi analysis in Minitab application. Therefore, according to the Signal to Noise Ratio data, the optimum values for cutting force are 60 m/min, 0.05 mm/rev and 0.5 mm for cutting speed, feed rate and depth of cut, respectively. In 10% cutting fluid and water solution atmosphere experiments, the optimum values for cutting force according to Signal to Noise Ratio are 90 m/min, 0.05 mm/rev and 0.5 mm for cutting speed, feed rate and depth of cut, respectively.

ANOVA analyses were performed to examine the effect of machining parameters on the cutting force data obtained under dry cutting conditions. The degree of influence of process parameters under dry cutting and cutting fluid conditions is shown in Table 6.

Table 6. Degree of influence of process parameters on the cutting force under dry cutting and cutting fluid conditions

DRY	
Parameter	Impact ratio (%)
Cutting speed	7,2
Feed rate	27,58
Depth of cut	64,61
MQL	
Parameter	Impact ratio (%)
Cutting speed	1,44
Feed rate	11,64
Depth of cut	84,29

Table 6 shows that the depth of cut is the most effective parameter on the cutting force in the study carried out under cutting fluid and dry cutting conditions.

The reliability rate of the study carried out in dry cutting atmosphere was found to be 97.37% by ANOVA analysis. In the study using cutting fluid, the reliability rate was found to be 99.4%.

Similar to our result, Akgün M., et al. reported that the most effective parameter on cutting force is feed rate [16].

3.2. Temperature

The temperature values obtained in dry cutting and MQL and vegetable cutting fluid spraying atmospheres are given in Table 7. The results can be followed visually in Figure 4, which was created with the data in Table 7. As can be seen from Table 7, the effect of the cutting atmosphere was affected by the process parameter values.

Table 7. Temperature values and percentage of difference

No.	**DRY**	**MQL**	**Difference (%)**
1	125	71,8	42,56
2	188	48,1	74,41
3	292	215	26,37
4	146	70	52,05
5	252	159	36,90
6	144	144	0
7	197	142	27,92
8	194	152	21,65
9	188	118	37,23

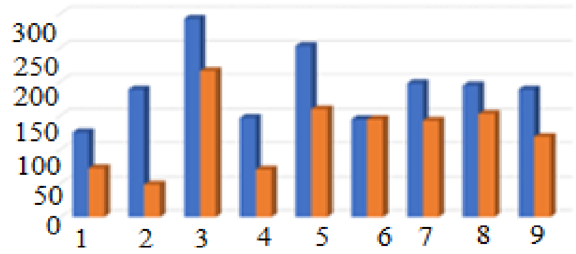

Figure 4. Temperature values (blue: dry, orange: MQL)

All of the measured temperature values of the parts processed in dry cutting environment during the process are higher than the temperature values measured in the cutting fluid atmosphere. This is actually an expected result; it is thought that the cutting fluid used removes the heat generated in the cutting zone.

Minitab application was used to examine the effect of processing parameters. Minitab application was used separately for each atmospheric condition. Signal-to-noise ratio was obtained through the Minitab application and the most appropriate processing values were obtained. The Signal to Noise ratio table obtained for cutting force under dry cutting and cutting fluid conditions is given in Table 8 and the ratio graph is shown in Figure 5.

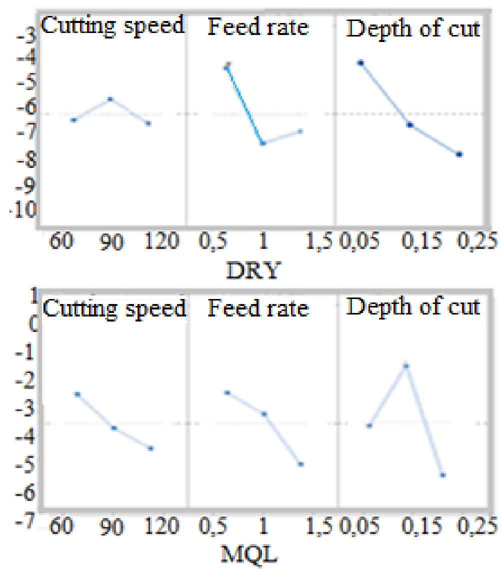

Figure 5. Signal to noise ratio plot of temperature values in dry machining and cutting fluid atmosphere

Table 8. Temperature signal-to-noise ratio values in dry machining and cutting fluid atmosphere

No.	Cutting speed	Feed rate	Depth of cut
DRY			
1	-39,14	-39,02	-41,31
2	-41,37	-40,44	-37,33
3	-42,71	-43,75	-44,57
MQL			
1	-45,58	-43,70	-43,62
2	-44,83	-46,20	-44,75
3	-45,71	-45,99	-47,74

In dry atmosphere tests, the optimum values for temperature according to the Signal to Noise Ratio are 90 m/min, 0.05 for mm/rev and 0.5 mm for cutting speed, feed rate and depth of cut, respectively. In the environment where cutting fluid is used, the optimum values for temperature according to Signal to Noise Ratio are 60 m/min, 0.05 to mm/rev and 1 mm for cutting speed, feed rate and depth of cut, respectively.

ANOVA analyses were performed to examine the degree of influence of process parameters on the temperature data obtained under dry cutting conditions. Table 9 shows the effect of process parameters under dry cutting and cutting fluid atmosphere conditions.

Table 9. Effect of process parameters on temperature in dry cutting and cutting fluid atmosphere

Parameter	Impact ratio (%)
DRY	
Cutting speed	4,41
Feed rate	28,16
Depth of cut	58,23
MQL	
Cutting speed	2,96
Feed rate	25,60
Depth of cut	63,37

In the experiments carried out in dry cutting and cutting fluid atmosphere, the most effective parameter on the temperature values was the depth of cut in both working environments (Table 9).

The reliability ratio study performed with the measured temperature data was found to be 91.93% in dry cutting ANOVA analysis and

90.80% in the environment where cutting fluid was used.

3.3. Surface roughness

Surface roughness values measured at different cutting atmospheres are given in Figure 6.

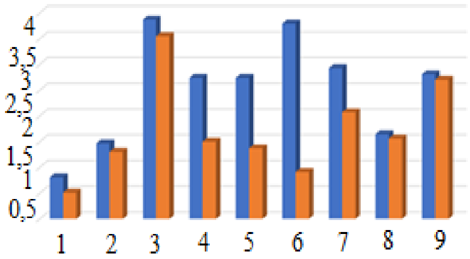

Figure 6. Surface roughness values (blue: dry, orange: MQL)

When the surface roughness values obtained from different cutting environments were analyzed, it was determined that the values measured in dry cutting atmosphere were higher.

Minitab application was used to examine the effect of processing parameters. Minitab application was used separately for each atmosphere condition. Signal-to-noise ratio was obtained through the Minitab application and the most appropriate machining values were obtained. The Signal to Noise ratio graph obtained for surface roughness values under dry cutting and cutting fluid conditions is given in Figure 7 and the ratio table is given in Table 10.

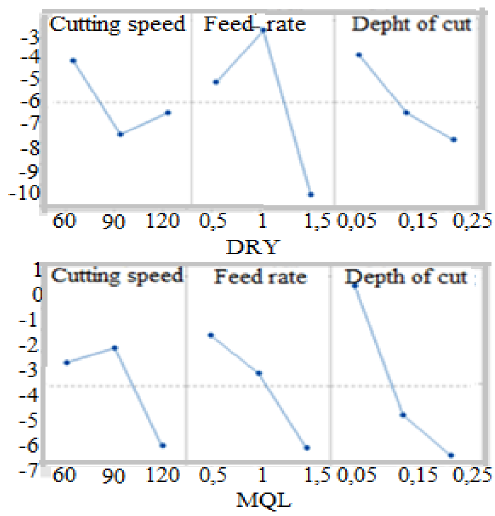

Figure 7. Signal to Noise ratio plot generated from surface roughness data obtained from dry cutting and machining in cutting fluid atmosphere

Table 10. Surface roughness signal to noise ratio values in dry cutting and cutting fluid atmosphere

DRY			
No.	Cutting speed	Feed rate	Depth of cut
1	-4,41	-4,15	-5,40
2	-7,89	-6,80	-3,03
3	-6,78	-8,04	-10,54
MQL			
1	-2,47	-0,94	-1,24
2	-1,81	-4,80	-2,95
3	-6,19	-6,60	-6,27

In dry atmosphere experiments, the optimum values for surface roughness according to Signal to Noise Ratio are 600 m/min, 0.05 mm/rev and 1 mm for cutting speed, feed rate and depth of cut, respectively. In cutting fluid atmosphere experiments, the optimum values for surface roughness according to Signal to Noise Ratio are 90 m/min, 0.05 mm/rev and 0.05 mm for cutting speed, feed rate and depth of cut, respectively.

ANOVA analyses were performed to examine the degree of influence of the process parameters on the surface roughness data obtained under dry cutting conditions. Table 11 shows the degree of influence of process parameters in dry cutting and cutting fluid atmosphere conditions

Table 11. Effect of process parameters on surface roughness in dry cutting and cutting fluid atmosphere

DRY	
Parameter	Impact ratio (%)
Cutting speed	5,50
Feed rate	62,05
Depth of cut	8,72
MQL	
Parameter	Impact ratio (%)
Cutting speed	15,37
Feed rate	45,91
Depth of cut	38,72

The most effective parameter for the surface roughness values obtained in both dry cutting atmosphere and MQL cutting conditions is the feed rate. Similarly, in their study, Subbaiah K.V., et al [17]. determined that the most effective parameter on surface roughness was feed rate (Table 11).

The reliability rate of the study was found to be 76.27% with the ANOVA analysis and 83.92% in the cutting fluid atmosphere.

4. Conclusion

The effects of the machining parameters used in the machining of pure titanium material in different cutting atmospheres on surface roughness, cutting force and temperature were investigated and the following results were obtained:

- It was found that the cutting force values were affected by the cutting conditions and the measured cutting force value was higher in dry cutting atmosphere. The difference between the cutting force data obtained in different cutting atmospheres is 64.97% and the smallest difference is 4.57%.

- It was determined that the most important effect on the cutting force data in dry cutting atmosphere was 84.29% of the depth of cut and the most important effect on the cutting force data in MQL cutting atmosphere was 64.6% of the depth of cut.

- The effect of feed rate on cutting force increased from 11.64% to 27.58% with MQL. For cutting speed, it increased from 1.44% to 7.20%.

- Due to the good wetting achieved with MQL, the average improvement in cutting force values was 23.98%.

- In the analysis of the parameters affecting the cutting force, the measured results were obtained with a high probability of accuracy. The overall probability of accuracy of the obtained results is around 97%.

- It was found that the temperature measured in the primary cutting zone increased with increasing depth of cut values and MQL was more effective on the temperature reduction rate. It is thought that fluid velocity, pressure and removal of heat from the environment with chips are effective in the temperature reduction of MQL.

- The most influential machining parameter on temperature data is depth of cut with 63.37% in dry cutting atmosphere, while The most effective machining parameter in the MQL machining atmosphere is the depth of cut with 58.23%.

- As cutting speed and the depth of cut increase, the temperature also increases and this has a negative effect on the surface roughness. In dry cutting atmosphere, when the results obtained from the surface roughness measured at the end of machining are analyzed, the most effective parameter is the feed rate with 62.05%.

- The accuracy data of the temperature values measured in the cutting zone are on average 85% accurate. This means that the results are highly reliable.

- When the surface roughness values measured after machining were analyzed, the most effective parameter was determined as feed rate by ANOVA analysis. As the feed rate, which refers to the movement of the cutting tip on the material to be cut in one cycle during production in the machining process, increases, the roughness on the material will increase due to the increase in the distance between the two feed steps.

Article Information Form

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Authors' Contribution
The authors contributed equally to the study.

The Declaration of Conflict of Interest/ Common Interest
No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval
This study does not require ethics committee permission or any special permission.

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