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MQL 알루미늄 선삭가공의 표면거칠기

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Surface Roughness of Turned Aluminum in MQL

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기계가공은 절삭 부위의 냉각작용과 윤활작용을 위해 절삭유를 많이 소모한다. 절삭유는 염소계의 극압첨가제 등이 함유되어 있어 작업자들에게 유독할 뿐만 아니라 대기의 오염을 초래하여 청정생산을 저해하게 되므로 이런 전통적인 방법은 작업자의 직업병으로부터 보호와 환경보호를 위하여 새로운 가공방법으로 변경되어야만 한다. MQL 기계가공 방법은 절삭유를 아주 소량 소모하므로 청정생산을 위한 대안으로 떠오르고 있지만 많은 작업자들이 이에 대한 기술적인 확신이 부족하여 이 방식의 사용을 주저하고 있다. 본 연구는 MQL 가공 방식에서 가공의 특성을 파악하여 표면거칠기에 영향을 미치는 인자와 범위를 찾고자 다양한 실험을 계획하고 그 결과를 분석하였다. 실험의 계획에서는 각 가공의 특성을 잘 나타낼 수 있는 인자와 수준을 선정하고, 다양한 상황의 결과를 분석하여 MQL 가공의 특성과 최적의 가공조건을 도출하였다. 본 연구의 실험 및 분석의 결과로서, 절삭 파라미터와 그의 수준이 가공특성을 잘 반영할 수 있도록 적절히 선택된다면 MQL 기계가공은 표면거칠기 향상 및 원가절감이나 환경보호 측면에서 절삭유 윤활방식을 대체하는 green manufacturing을 위한 대안이 될 수 있음을 보였다.

Keywords : MQL Machining, Turning, Surface Roughness, Aluminum

1. Introduction

Modern metal working industries manufacture precision parts with delicate dimensions. The main process used for precision manufacturing is machining, which is good for producing duplicate parts with tight tolerances in mass production. For this reason, a lot of modern manufacturing industries use this operation. But this process consumes a large amount of cutting fluid for cooling and lubrication at the contact point of the tool and the work-piece. Cutting fluid contains toxic material which is very harmful to humans. It contains additives for extreme pressure which are noxious, including chlorine, sulfur, phosphorus, etc [11].

Cutting fluid causes occupational disease in the respiratory organs of workers in machining shops. Because cutting fluid plays roles in both cooling and lubrication, it cannot be withdrawn from precision machining. Cutting fluids costs high in the machining practice. The cost of lubricants is about 17% of the total machining cost [7]. It charges about four times higher than the tool cost in machining. When planning to reduce the production cost in machining, the lubrication is the most likely item to be

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considered. To help to overcome the problems mentioned in the previous paragraph, green machining comes as an alternative. Green machining includes dry machining [7, 12], MQL (Minimum Quantity Lubrication) machining [2, 8], and cryogenic machining. Dry machining does not use cutting fluid at all, which causes problems with lubrication and cooling. This approach generates high heat and much friction at the point of machining. As a result, it reduces tool life in machining. Cryogenic machining causes the technical problem of frosting on the surface of the pipe line in which chilled wind flows in the equipment. This problem lowers the effective cool-down, and does not produce effectively machined parts as a result.

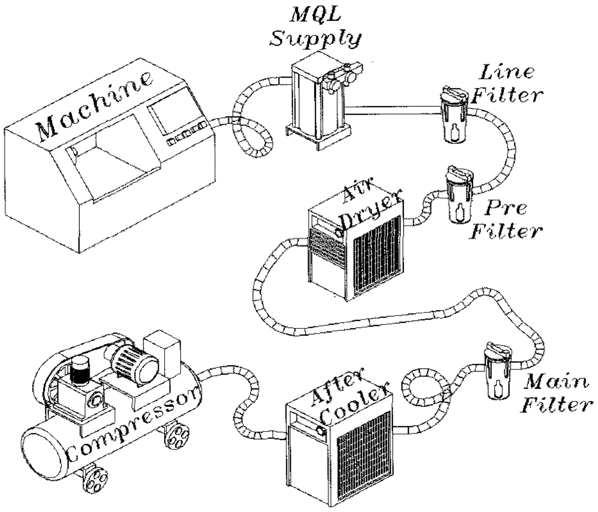
MQL machining fulfills the requirements of both cooling and lubrication, but it consumes a minimum of cutting fluid. Thus, MQL machining is a good alternative not only for green machining, but also for cost efficiency. Since MQL machining consumes a small amount of lubricant, for example 10mL/h., the possibility of air pollution is much less than with fluid cutting.

Even though MQL machining is a good method for precision manufacturing, operators are unwilling to adopt it in the machining practice. The reason is that they do not have sufficient technical proof of the results of MQL machining. Thus, industries do not popularly use MQL machining in precision machining. This research applies MQL machining to provide some results aimed at convincing operators in machining.

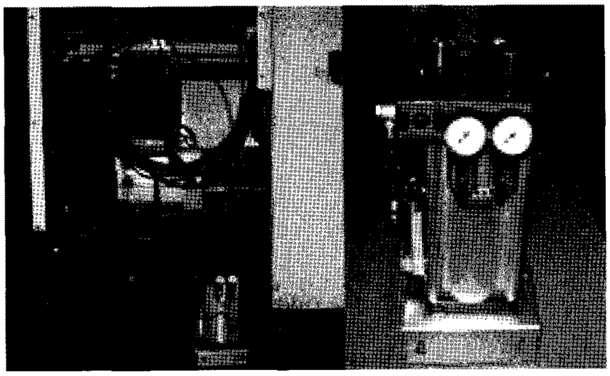
The objective of this experiment is to optimize surface roughness in MQL machining. Experimental factors and levels in turning are selected to perform experiments. This paper draws conclusions through analyzing the experimental data. The final results are meant to inform operators in order that they will be convinced of the high quality of the surface roughness in MQL machining.

2. Experimental Setup

MQL machining requires special equipment for atomizing lubricant. An air compressor, suppliers, and filters are the major apparatus for MQL machining. <Figure 1> and <Figure 2> show experimental setups and an MQL supplier equipped to an NC lathe [6].



<Figure 1> Experimental setup for MQL



<Figure 2> MQL Supplier Equipped

Since the air in machining shops contains a lot of dust particles, these should be removed to supply clean air. A cleaning system is equipped with several filters to remove them. The filters' work is associated with the size of the dust. In addition, an air dryer is required for cleaning the system. It eliminates moisture contained in the supplied air. <Table 1> shows the specification of MQL. The lubricant in MQL machining is supplied in aerosol type which consists of very small droplets. The size of the droplets is affected by the amount of air and oil which are mixed in the MQL supplier. Vegetable oil is used as a lubricant for proper mixture and control with ease.

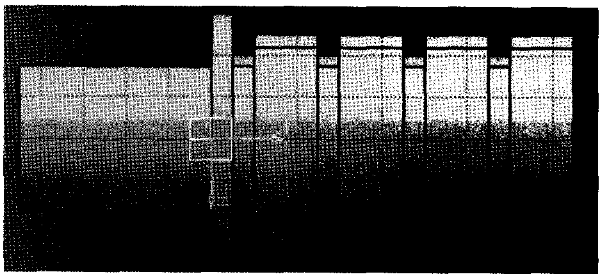
<Table 1> Specification of MQL Supply

Oil droplet size (㎛)	Aerosol quantity (㎖/h)	Air consumption (Nl/min)
0.5	5~150	140~300

3. Machining Condition

This research performs experiments for MQL turning on a CNC lathe. The objective is to find machining characteristics and optimal machining parameters producing low surface roughness in MQL machining.

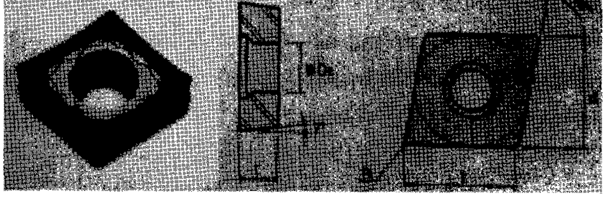
The geometry of the specimen is shown in <Figure 3>. The right side of the bar is machined and the roughness of its surfaces is measured. The diameter of the specimen is 60mm and it is divided by four space grooves which are 5mm in depth and 5mm in width. The length of the four machining surfaces is 15mm each [3].



<Figure 3> Geometric Shape for the Specimen

The cutting material used in the experiment is aluminum 7075, which is aluminum alloy and has recently been used for aircraft components. The material is tougher and higher in strength than aluminum 6010 which was commonly used in aircraft production. The chemical composition of the AL 7075 is about 94% aluminum. Remainders include copper, magnesium, iron, etc.

The cutting tool material adopted in the research is K10 grade tungsten carbide-cobalt alloy in insert type. It is rhombus-shaped with a groove for the chip breaker. <Figure 4> shows the geometry of an insert.



<Figure 4> Shape of an Insert

The roughness of the machined surface is measured on a measuring machine in Ra. The measurement follows Korean Industry Standard (KS) and adopts Center Line Average method. <Table 2> shows standard values for measuring details.

<Table 2> Standard Values for Measurement

Cut off (mm)	Sampling length (mm)	No. of sampling	Evaluationlength (mm)
0.8	2.5	5	12.5

One machined surface for the experiment is measured four times in different positions within one machined area. The specimen is rotated 90 degrees for every measurement to take quadruple data.

4. Experimental Design

The purpose of this research is to find optimal machining conditions for MQL turning. Thus, this experiment should select controllable experimental factors that affect surface roughness on the turned area. The most important factor for the experiment is the amount of MQL because it is meant to find any effects of MQL on the roughness of machined surfaces. The next one is air pressure that will carry the lubricant to a cutting point. Cutting speed, feed rate, and depth of cut are additionally selected as experimental factors. Other factors that affect surface roughness for the study are cutting tool geometry, work-piece, lathe used, etc. Since they are uncontrollable and noisy factors, they are not considered as experimental factors, and hence removed [4].

Measured data of surface roughness are collected and analyzed to find any effective factors in producing low roughness. The variances of measured data and signal to noise ratio (S/N) are calculated and analyzed to find the main effects [9].

5. The Experiments for MQL Machining

This research plans four sets of experiments according to different purposes respectively. These experiments are designed based on the different experimental factors and levels adopted.

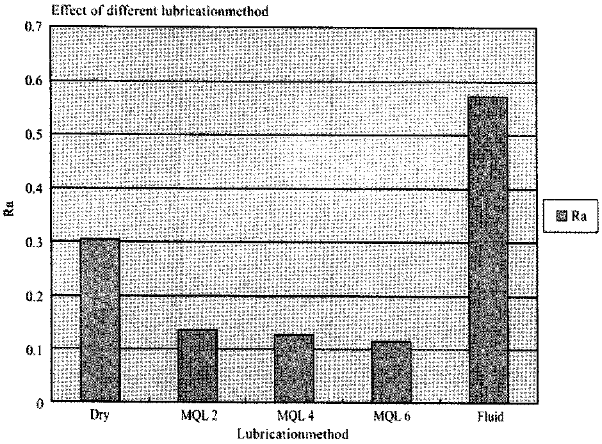
5.1 Experiments for MQL Effect

This experiment plans to find any effects of the amount of MQL on the machined surface. The experiment compares the roughness data produced from MQL turning with data from non-MQL turning. Fluid cutting and dry cutting are non-MQL lubricating machining. Thus, the lubrication method is selected as one of the experimental factors. Other experimental factors are cutting speed, feed rate, depth of cut, and air pressure. The experimental levels are selected by utilizing previous research [5]. The experimental levels of the factors are each set at the optimal value that can be found in the literature [4]. <Table 3> shows experimental factors and their levels.

<Table 3> Design Array of Experiment

No	Speed (RPM)	Feed (mm/rev)	DOC (mm)	Air (bar)	Lubrication
1	1500	0.01	1	3	Dry
2	1500	0.01	1	3	Fluid
3	1500	0.01	1	3	MQL Nozzle size 2
4	1500	0.01	1	3	MQL Nozzle size 4
5	1500	0.01	1	3	MQL Nozzle size 6

<Figure 5> shows that surface roughness data produced by the MQL method is better than any data by the non-MQL methods. This result comes under the machining conditions of the parameters specified in the design array for this experiment in <Table 3>. Generally, fluid cutting is dominantly adopted in machining practice. But the result of the investigation shows that its surface roughness is the worst. From this study, this paper insists that MQL machining is a good alternative to replace conventional lubrication if the machining parameters are properly selected. The next experiment is planned to investigate any effects of major machining parameters on surface roughness under MQL machining conditions.



<Figure 5> Effect of different lubrication

5.2 Experiments with Factors of Major Machining Parameters

In this experiment, the research aims to find any effects on surface roughness produced by three major machining parameters. They are the most important parameters in machining practice: cutting speed, feed rate, and depth of cut. This study investigates the role of the major parameters under MQL machining circumstances. <Table 4> shows the experimental factors and their levels. Since the feed rate in machining is a sensitive parameter for surface roughness, its level is increased by a small amount to investigate its effects to surface roughness [13]. In order to reduce the number of runs in the experiment, this research designs 9 runs adopting L9 of the Taguchi method [10].

<Table 4> Experimental Factors and Levels

	Speed (RPM)	Feed (mm/rev)	DOC (mm)
1	1500	0.01	1.0
2	2000	0.02	1.5
3	2500	0.03	2.0

Experimental data are collected from the measurement. S/N ratio, mean value of the data, and ANOVA (ANalysis Of VAriances) are calculated and they are shown in <Tables 5>, <Figures 6> and <Figures 7> are data plots for S/N ratio and data means. From these figures, the result of this investigation under MQL machining conditions is similar to the traditional machining experiment [1]. That is, a small value of feed rate produces low surface roughness.

<Table 5> Response Table for S/N Ratios

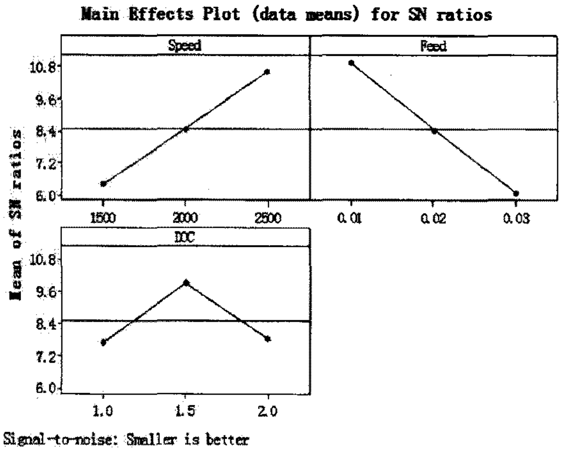
Level	Speed	Feed	DOC
1	6.397	10.961	7.718
2	8.487	8.440	9.901
3	10.601	6.084	7.866
Delta	4.204	4.876	2.183
Rank	2	1	3

<Table 6> Response Table for Data Means

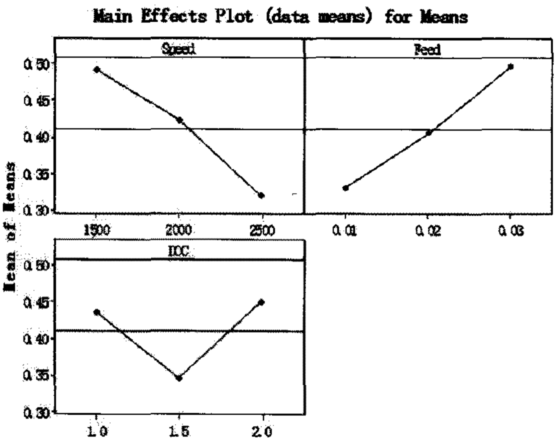
Level	Speed	Feed	DOC
1	0.4917	0.3303	0.4376
2	0.4223	0.4064	0.3462
3	0.3198	0.4971	0.4500
Delta	0.1719	0.1668	0.1038
Rank	1	2	3

<Table 7> ANOVA Table

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Speed	2	26.514	26.514	13.257	0.42	0.702
Feed	2	35.682	35.682	17.841	0.57	0.636
DOC	2	8.930	8.930	4.465	0.14	0.875
Error	2	62.425	62.425	31.212		
Total	8	133.550				



<Figure 6> Main Effect Plot for S/N Ratios



<Figure 7> Main Effect Plot for Data Means

In this experiment, the level of the feed rate is between 0.01mm and 0.03 mm per revolution. From the response table for data means, a low feed rate produces low surface roughness. This is in accordance with the principles of machining. Generally, the higher the feed rate, the worse the roughness [1]. From the response table for S/N ratio, the feed rate is the most sensitive factor. ANOVA in <Table 7> does not show that any factors are significantly large in variances. This is because the differences between levels of the feed rate adopted in the study are exceedingly small. In order to investigate machining characteristics with a high rate of feed, the next experiment should adopt a higher value of feed than that of this one.

5.3 Experiment with more Factors

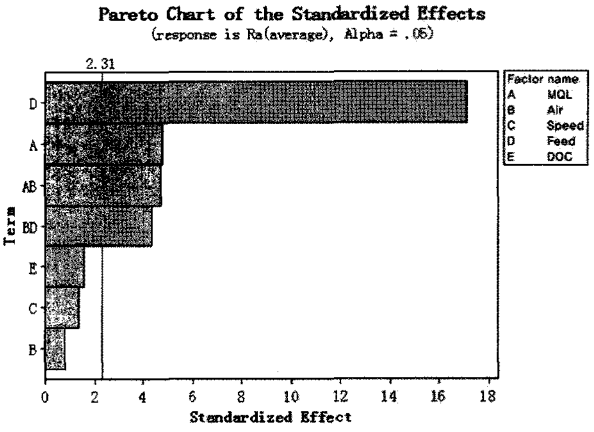
This research plans to find any effects on surface roughness caused by amount of MQL and air pressure for supplying MQL. The experiment designs five factors and two levels for each experimental factor. <Table 8> shows the design array for this study.

<Table 8> Experimental Factors and Levels

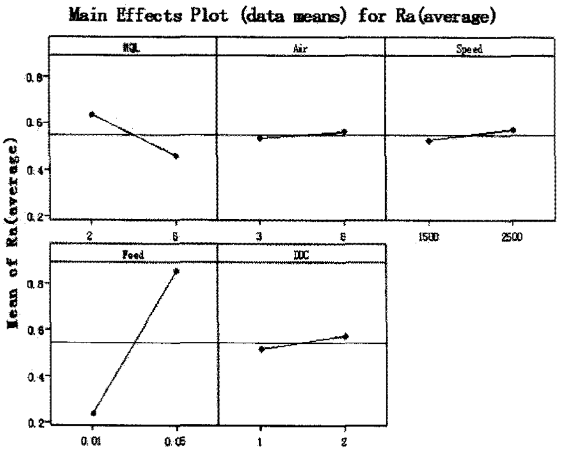
	Nozzle (mm)	Air Pressure (bar)	Speed (RPM)	Feed (mm/rev)	DOC (mm)
1	2	3	1500	0.01	1.0
2	6	8	2500	0.05	2.0

The fractional factorial design reduces the number of experimental runs, which is 16 at the experiment, reduced in half. This is because the main effect is primarily important and higher orders of interactions are not expected.

From analysis of the experiment, <Figure 8> shows a Pareto Chart for the standardized effect. Feed rate is the most significant factor from the result. The amount of MQL, the interaction of MQL and air pressure, and the interaction of air pressure and feed rate also have significant effects on surface roughness. <Figure 9> shows that the main effect plot of data means and feed rate 0.01 produces very low roughness.

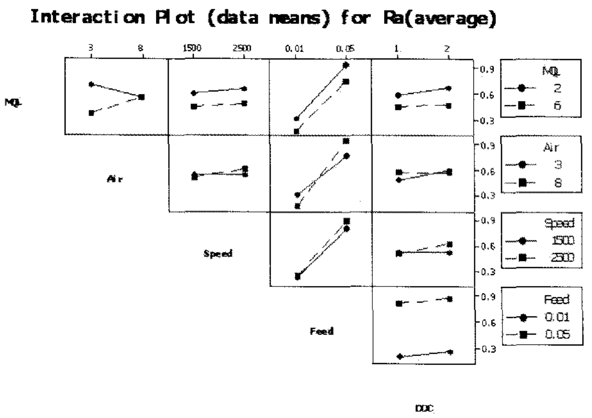


<Figure 8> Pareto Chart of the Standardized Effects

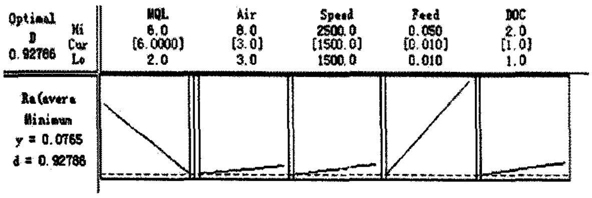


<Figure 9> Main Effect Plot for Data Means

<Figure 10> shows an interaction plot for data means. From the figure, we see the interaction of the amount of MQL and air pressure is effective. Feed rate also interacts with air pressure. Even though eight bar of air pressure is suggested, 3 bar is adopted for low surface roughness in the response optimization. This is because of the effectiveness of interaction. <Figure 11> is for response optimization. MQL 6, Air 3, Speed 1,500, Feed 0.01, and DOC 1 are selected to optimize the surface roughness. In this combination of levels for the factors, the lowest roughness expected is 0.0765 micro meters.



<Figure 10> Interaction Plot for Data Means



<Figure 11> Response Optimization

5.4 Experiment with more Levels

This experiment modifies the range of experimental levels which are selected in the previous experiment. The next <Table 9> shows the experimental design with higher levels of feed rate. Previous experiments reach a conclusion that feed rate is the most sensitive and effective for surface roughness.

<Table 9> Experimental Factors and Levels

	Nozzle (mm)	Air (bar)	Speed (RPM)	Feed (mm/rev)	DOC (mm)
1	2	3	1500	0.05	1.0
2	4	6	2000	0.1	1.5
3	6	8	2500	0.15	2.0

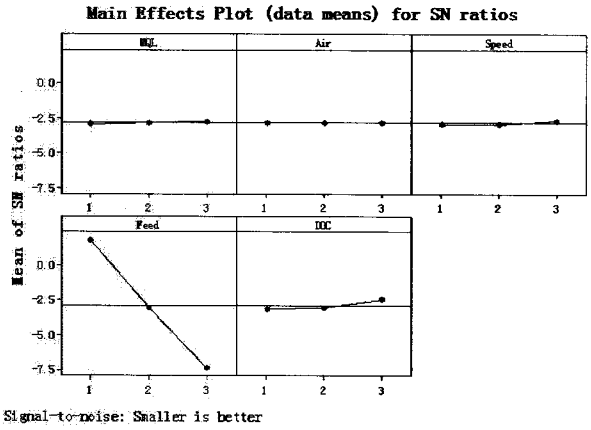
Because the feed rate is the most sensitive factor from the experiment described in the previous section, this experiment changes its levels for a wider range than the previous ones. Total number of experiment is reduced to 27 by using Taguchi method L27. This research calculates S/N ratio and response table for mean of data .The following tables and figures show the response table for signal to noise ratios and data means, and their plots. From the response table, feed rate 0.05mm/revolution produces the lowest roughness, which is 0.8144 micro meters.

<Table 10> Response Table for S/N Ratio

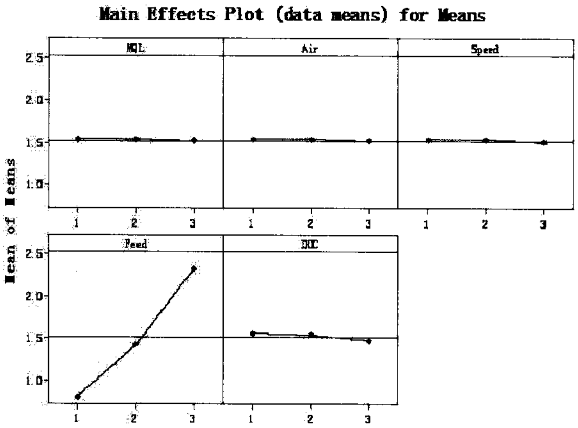
Level	MQL	Air	Speed	Feed	DOC
1	-2.993	-2.898	-2.980	1.776	-3.127
2	-2.868	-2.876	-2.967	-3.099	-3.035
3	-2.811	-2.898	-2.725	-7.350	-2.510
Delta	0.182	0.021	0.255	9.126	0.617
Rank	4	5	3	1	2

<Table 11> Response Table for Means

Level	MQL	Air	Speed	Feed	DOC
1	1.5386	1.5266	1.5372	0.8144	1.5546
2	1.5265	1.5254	1.5383	1.4294	1.5507
3	1.5107	1.5238	1.5003	2.3319	1.4705
Delta	0.0279	0.0028	0.0380	1.5174	0.0841
Rank	4	5	3	1	2



<Figure 12> Main Effect Plot for S/N Ratios



<Figure 13> Main Effect Plot for Data Means

From the collected data, this study calculates and analyzes variances in the ANOVA table, which is shown in <Table 12>. The previous tables and figures show feed rate is the most sensitive and important factor for surface roughness. When the feed rate is increased from 0.05mm/revolution to 0.15mm/revolution, the surface roughness is increased from 0.8144 to 2.3319 micro meters. As this means that the feed rate has a great effect on surface roughness, one should thoughtfully consider this effect in changing the feed rate.

<Table 12> ANOVA Table

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Nozzle	2	0.0035	0.0035	0.0018	0.34	0.718
Air	2	0.0000	0.0000	0.0000	0.00	0.996
Speed	2	0.0084	0.0084	0.0042	0.81	0.462
Feed	2	10.4859	10.4859	5.2429	1010.41	0.000
DOC	2	0.0406	0.0406	0.0203	3.91	0.041
Error	16	0.0830	0.0830	0.0052		
Total	26	10.6214				

5.5 Experimental Results and Discussions

From the results described in the previous paragraphs, this research summarizes as the followings. MQL machining produces low surface roughness compared with non-MQL machining if the levels of major machining parameters are properly selected. Since the very small values of feed do not sufficiently show machining characteristic in surface roughness, the increase between levels of factors should be fairly large. From the Pareto chart for the experiment, feed is the most sensitive parameter to reduce surface roughness. The major parameters interact with each other, but their degrees are not serious. From the experiment with five major factors and three levels for each factor, feed and depth of cut significantly perform a role to reduce surface roughness. The possible low value of surface roughness, 0.0675 micro meters, is produced when MQL 6, Air 3 bars, Speed 1500mm/rev., Feed 0.01mm/rev., and Depth of Cut 1mm are selected.

6. Conclusions

The amount of MQL is surely the effective experimental factor for surface roughness of the machined part. The surface roughness produced by MQL machining is superior to the ones produced by non-MQL machining in this study. The feed rate has a key role to reduce the surface roughness in MQL turning, which is also true in conventional machining. But the amount of MQL and the air pressure for carrying MQL are neither sensitive nor effective. Thus, MQL machining produces good surface roughness when the levels of major machining parameters are selected properly. Consequently, MQL machining is a great alternative for green manufacturing and, thus, fluid should be replaced by MQL in the machining practice. This method reduces both the machining cost and air pollution.

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