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Surface roughness and cutting force prediction in MQL and wet turning process of AISI 1045 using design of experiments †

Young Kug Hwang and Choon Man Lee*
Department of Mechanical Design & Manufacturing Engineering, Changwon National University,
#9 Sarim-dong, Changwon-si, Gyeongsangnam-do, 641-773, Korea

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Abstract

This paper presents an investigation into the MQL (minimum quantity lubrication) and wet turning processes of AISI 1045 work material with the objective of suggesting the experimental model in order to predict the cutting force and surface roughness, to select the optimal cutting parameters, and to analyze the effects of cutting parameters on machinability. Fractional factorial design and central composite design were used for the experiment plan. Cutting force and surface roughness according to cutting parameters were measured through the external cylindrical turning based on the experiment plan. The measured data were analyzed by regression analysis and verification experiments were conducted to confirm the results. From the experimental results and regression analysis, this research project suggested the experimental equations, proposed the optimal cutting parameters, and analyzed the effects of cutting parameters on surface roughness and cutting force in the MQL and wet turning processes.

Keywords: MQL turning; Optimal cutting parameters; Fractional factorial design; Central composite design; Surface roughness and cutting force prediction

1. Introduction

Cooling lubricants are used in machining processes to reduce friction at the tool-chip and tool-workpiece interfaces, cool both chip and tool, and remove chip. They have a strong effect on shearing mechanisms and, consequently, on machined surface quality and tool wear [1]. For companies, the costs related to cutting fluids represent a large amount of total machining costs. Research has found that the costs related to cutting fluids are frequently higher than those related to cutting tools. Moreover, cooling lubricants have been found to cause health and social problems for workers, related to lubricant use and correct disposal [1-7].

Therefore, many researchers have focused on environment friendly machining technology. Environment friendly machining technologies can be classified into dry and semi-dry machining technologies according to consumption of cutting fluids [2]. It is important to consider environmental factors (minimization of waste and human toxicity, and saving of cutting fluid) and economical factors (saving energy and improvement of production efficiency) at the same time.

Significant progress has been recently made in dry and semi-dry machining; MQL (minimum quantity lubrication) machining, in particular, has been accepted as a successful semi-dry application because of its environment friendly characteristics. Some good results have been obtained with this technique [8-16]. Machado et al. [8] conducted an experiment on turning AISI 1040 using this technique and concluded that, in cases of surface finish, chip thickness and force variation, MQL affected all beneficially compared to results obtained with the flood coolant. Dhar et al. [9, 10] used this technique in the turning process and concluded that, in some cases, MQL has been shown to be better than flood coolant. Braga et al. [11] reported that the drilling process of aluminium-silicon alloys using MQL technique presented either similar or better quality than those obtained with the conventional wet technique.

As described above, many researchers are studying the economical and environmental efficiency of MQL machining by comparison experiments within different cooling-lubrication environments. However, in the case of MQL machining, not many studies have been done on the effects of cutting parameters on the machinability (cutting force, surface roughness, tool life, etc.) and selection of optimal cutting conditions. In other words, the optimal cutting conditions and the effect of cutting conditions on machinability could vary according to different cooling-lubrication environments, but the studies regarding those topics are not sufficient. The best machining

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*Corresponding author. Tel.: +82 55 213 3622, Fax: +82 55 267 1160
E-mail address: cmlee@changwon.ac.kr

Table 1. Instruments and specifications.

Instrument	Company	Specification
Turning center	Hwacheon	Hi-ECO 10
Dynamometer	Kistler	9257B
Charge amplifier	Kistler	5019A
Surface roughness tester	Mitutoyo	Surftest SV-624
MQL supplier	VOGEL	Vario UFV 10-001

technologies will not guarantee the best machining results unless the optimal cutting parameters are selected.

This study examines turning processes using the MQL of the AISI 1045 work material and cutting fluid, following the previous study on MQL turning process of the material A1 6061 [15]. While the previous study focused on the finding of the optimum cutting parameters for MQL turning of A1 6061, this study intends to find the optimum cutting parameters for the most commonly used material for machine structures. Furthermore, the study goes on to include a wet machining environment to the existing MQL machining environment, so that the effects of both machining environments can be comparatively analyzed. For these purposes, FFD (fractional factorial design) and CCD (central composite design) were used for the experiment plan. Cutting force and surface roughness according to cutting parameters were measured through the external cylindrical turning of AISI 1045 based on the experiment plan. The measured data were analyzed by regression analysis, and verification experiments with random conditions were conducted to confirm the suggested experimental model.

2. Experimental equipment and procedure

2.1 Experimental equipment

Table 1 shows the experimental equipment used in this study and Fig. 1 shows the machining system used in the experiments. The machining system was composed of a lathe, MQL supplier, air cleaning system and compressor. In case of the MQL supplier used in this study, the manufacturer's recommend supplied air pressure is over 7bar [17]. Generally, machine shops have supplied air pressure around 5bar. This does not satisfy the manufacturer's recommended air pressure (over 7bar). Therefore, an air cleaning system and air compressor were installed to solve problems related to air-pressure, which was recommended by the MQL supplier manufacturing company but hard to achieve in ordinary machine shop environments. To minimize the effect of air quality on the experimental results, an additional air cleaning system was installed.

The MQL supplier is a Vario UFV10-001 manufactured by VOGEL, the German manufacturer; detailed specifications are referred to in ref. [17].

2.2 Workpiece and cutting tool

In the experiment, carbon steel AISI 1045 was used as workpiece. All the experiments were carried out on cylindrical samples with initial values of length and diameter equal to 100 and 58mm, respectively.

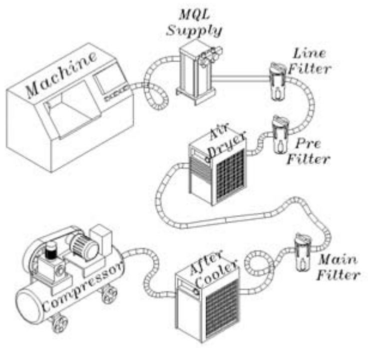


Fig. 1. Experimental set up.

As for the cutting tool, CNMG 120404 FG insert with a 0.4mm nose radius, which has carbide inserts coated with ISO classification k10, was used [18].

The insert was mounted on a tool holder with an approach angle of 5 degrees and entering angle of 95 degrees [18].

2.3 Experimental method

In the case of wet machining, research into machinability with various combinations of materials and tools has already been done by many researchers; it is even more important to consider the combination of optimal level of cutting parameters compared to the selection of cutting parameter types. However, MQL machining is still in the beginning stages and its research has not matured. Broader consideration of cutting parameter types that affect the machinability, and their optimal levels, should be taken into account to achieve high productivity and quality. To do this, a number of experiments should be done to confirm results. As already known, it is not easy to analyze the cutting process when many parameters are involved because each parameter has interaction effects. When there are many parameters to consider for the evaluation of the characteristics, and interaction effects between parameters is expected, it is very useful to use design of experiments. In this case, first, the parameters affecting the characteristics are analyzed by screening design, and the optimal combination of parameters is chosen by optimization design.

This paper used a two-level fractional factorial design to select the major parameters affecting the characteristics considered in this experiment. A central composite design from response surface method was used to analyze the effects of cutting conditions on the characteristics and to find the optimal cutting parameters in MQL and wet machining. Fig. 2 shows the experimental procedure.

Because machinability can vary according to the supplying direction and distance of the cutting fluids, in this experiment the distance between nozzle and insert tips was fixed at 11mm and the cutting fluids were supplied at a 30 degree angle. There has been research on machinability according to the supply direction and distance of the cutting fluids [12], but

Table 2. Experimental conditions for fractional factorial design.

Process parameters	
Factors	Levels
Cutting speed [m/min] Feed rate [mm/rev] Depth of cut [mm]	100, 300 0.1, 0.3 0.4, 1
MQL supply	
Factors	Levels
Supplied air pressure [bar] Nozzle diameter [mm]	4, 8 2, 6

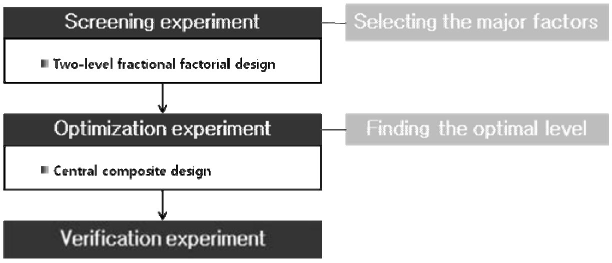


Fig. 2. Experimental procedure.

these effects were not considered in this study.

The cutting force was measured and recorded through a Kistler type 9257B dynamometer, a charge amplifier and PC software. The surface of the machined workpieces, defined through the Ra value, was measured using a Mitutoyo tester with cut-off value, sampling length, and evaluation length according to KS standards. All measurements were repeated three times, and the average value was taken as the final value.

3. Screening experiment

3.1 Design of screening experiment

A two-level fractional factorial design with resolution V, which is among the most widely used types of design in industry, was used for screening experiments [19-20]. The reason for the usage of resolution V was to analyze the main effect and two-factor interactions. Generally, in resolution V, the main effects are confounded with four-factor interactions, and two-factor interactions are confounded with three-factor interactions. If interactions higher than three-factor interactions can be ignored, the main effect and two-factor interactions can be analyzed.

Surface roughness was measured as a characteristic value. Five factors, which were selected based on previous experiments and references, were investigated in a 2^{5-1} design with the objective of learning how these factors affect surface roughness. The five factors were A=supplied air pressure, B=nozzle diameter, C=cutting speed, D=feed rate, and E=depth of cut. Each factor was run at two levels. The experimental conditions are given in Table 2.

3.2 Analyzing the screening experiment

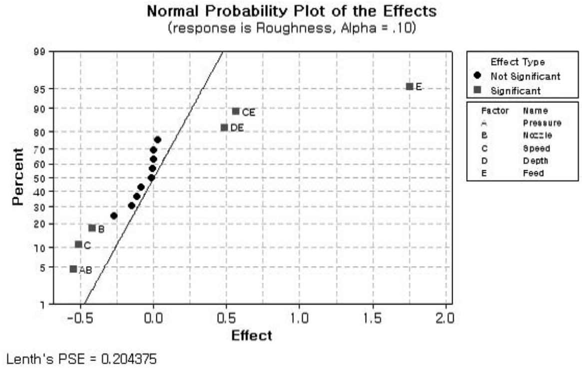


Fig. 3. Normal probability plot of the effects on surface roughness.

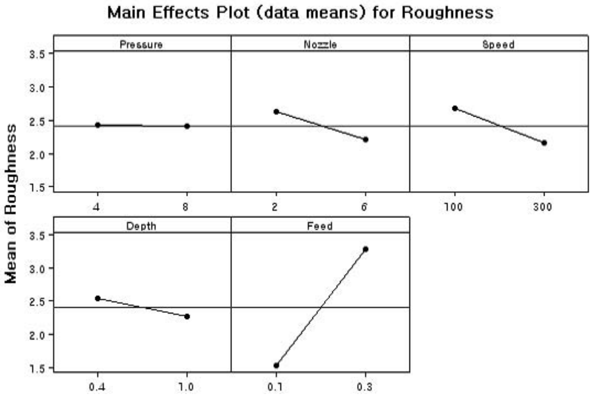


Fig. 4. Main effects plot for surface roughness.

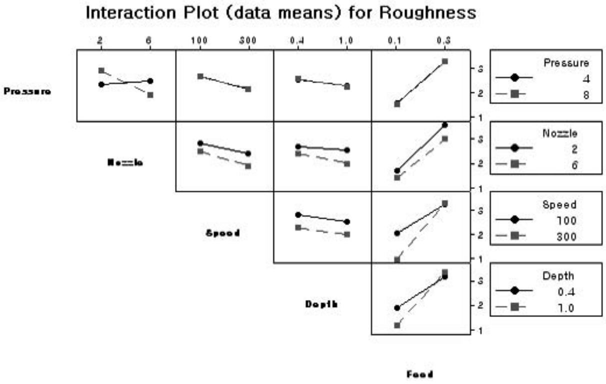


Fig. 5. Two-factor interaction plot for surface roughness.

To analyze the effects of individual factors on the surface roughness, the data obtained from the experiment were statistically analyzed with MINITAB software [21]. The estimation effects were set to the main effect and two-factor interactions. The significance level was set to 95%.

Fig. 3 presents a normal probability plot of the effect estimates from this experiment. This plot confirms that the main effects of B, C, and D and the AB, CD, and DE interactions are large.

Fig. 4 shows the main effect plot for surface roughness, and Fig. 5 is a two-factor interaction effect plot for surface rough-

Table 3. Experimental conditions for central composite design.

Process parameters	
Factors	Levels
Cutting speed [m/min]	50, 150, 250, 350, 450
Feed rate [mm/rev]	0.01, 0.02, 0.11, 0.2, 0.29
Depth of cut [mm]	0.1, 0.2, 0.7, 1.2, 1.7
MQL supply	
Factors	Levels
Nozzle diameter [mm]	2, 4, 6

ness. Among the main effects, D has the most important effect on surface roughness and C is the second. Factor A has little effect on the surface roughness. The interaction effects of AB, CD and DE are significant.

According to the above results, B, C, D, and E were chosen as the parameters affecting the surface roughness of the MQL turning operation in this paper.

4. Optimization experiment

4.1 Design of optimization experiment

Response surface method (RSM) is an optimal design method based on a statistical approach. In RSM, polynomial equations, which explain the relations between input variables and response variables, are constructed from experiments or simulations and the equations are used to find optimal conditions of input variables in order to improve response variables.

For the design of RSM, central composite design (CCD) was used in this experiment. CCD is widely used for fitting a second-order response surface. CCD consists of cube point runs, plus center point runs, and plus axial point runs [19]. The four factors (A=nozzle diameter, B=cutting speed, C=feed rate, D=depth of cut), which were selected in the screening experiment, were used in CCD. Table 3 shows the experiment design for optimization.

4.2 Analyzing the optimization experiment

In RSM, usually we are fitting the regression model to data from a designed experiment, and checking the adequacy of the regression model. In this paper, in order to establish a fitted regression model and estimate regression equations, a fitted model was selected as a full quadratic polynomial equation form that considers the response surface form regarding all the parameters. The adequacy of the fitted model was determined by a formal test for the lack of fit, residual analysis, and coefficient of determination of the fitted model [19, 20]. When a fitted model was not adequate, a new fitted model was constructed by the reduction of the response surface model, which is a pooling of insignificant terms from the ANOVA table.

To analyze the designed experiment results, commercial software of MINITAB was used.

4.2.1 The fitted model of MQL turning

The response surface model regarding cutting force in the MQL turning operation was fitted by pooling the interaction effects of AB, AC, AD and the square terms AA, BB, CC, those values are not significant. In the case of the fitted model, the formal test results show that the lack of fit was 0.295 and the coefficient of determination was 99.7%.

The fitted second-order response function is given by Eq. (1). The least squares method was used to estimate the parameters in the second-order response function.

$$F_{p\text{-}mql} = -17.88d^2 - 1.51n + 0.19c + 527.84f + 155.75d + 1.45cf - 0.15cd + 2147.36fd - 47.97 \tag{1}$$

where $F_{p\text{-}mql}$ is the principal cutting force, n is the nozzle diameter, c is the cutting speed, f is the feed rate, and d is the depth of cut.

The response surface model regarding surface roughness in the MQL turning process was fitted using the same method as in the case of the cutting force. The interaction effects of AB and square terms AA, DD were pooled. The formal test results show that the lack of fit was 0.001 and determination coefficient was 82.5%.

The fitted second-order response function of the surface roughness is given by Eq. (2).

$$R_{a\text{-}mql} = 17.819f^2 + 0.00004c^2 - 0.154n - 0.028c - 12.683f - 2.0197d + 0.783nf + 0.0198cf + 0.0045cd + 5.201fd + 6.469 \tag{2}$$

where $R_{a\text{-}mql}$ is the surface roughness, n is the nozzle diameter, c is the cutting speed, f is the feed rate, and d is the depth of cut.

4.2.2 The fitted model of wet turning

The response surface model regarding cutting force in wet turning was fitted by pooling the main effect of A and the interaction effects of AB, AC, AD and the square terms AA, BB and DD.

To check the adequacy of the fitted model, residual analysis, lack of fit and coefficient of determination were used. The lack of fit was 0.495 and the coefficient of determination was 99.7%. This means that the fitted model is adequate.

The second-order response function of cutting force in wet turning is given by Eq. (3).

$$F_{p\text{-}wet} = -995.73f^2 + 0.24c + 799.68f + 162.20d - 1.25cf -0.27cd + 2056.25fd - 73.59 \tag{3}$$

where $F_{p\text{-}wet}$ is the principal cutting force, n is the nozzle diameter, c is the cutting speed, f is the feed rate, and d is the depth of cut.

The response surface model regarding surface roughness in wet turning was fitted by pooling the main effect of A and the interaction effects of AB, AC, AD and the square terms AA and DD. In the evaluation of adequacy, the lack of fit was 0.001 and determination coefficient was 84.4%.

Eq. (4) shows the response function of surface roughness in wet turning.

$$R_{a\text{-}wet} = 61.784f^2 + 0.00005c^2 - 0.0455c - 34.375f - 4.956d + 0.0513cf + 0.0116cd + 12.507fd + 10.967 \quad (4)$$

where $R_{a\text{-}wet}$ is the surface roughness, n is the nozzle diameter, c is the cutting speed, f is the feed rate, and d is the depth of cut.

4.3 Selecting the optimal cutting parameters

Using the estimated regression model, the optimal conditions for the improvement of machinability in MQL and wet turning were selected and the individual parameters affecting the machinability were analyzed. The optimal combination of cutting parameters, including the minimization of cutting force and surface roughness, was selected using smaller-the-better characteristics.

4.3.1 MQL turning

Fig. 6 shows the effects of the individual cutting parameters on surface roughness and cutting force.

From Fig. 6, we can see that cutting force was influenced by cutting speed, feed rate, and depth of cut. The better cutting force was achieved with the smaller cutting speed, feed rate, and depth of cut; the relationship of these factors was linear. Even though the nozzle diameter had limited influence, a higher value of nozzle diameter resulted in less cutting force. In the case of surface roughness, cutting speed and feed rate greatly affected the surface roughness. Cutting speed and feed rate factors had a nonlinear relationship with surface roughness and showed a curved surface effect. There was a saddle point showing the optimal conditions.

If there are several response variables, combined desirability expressing common preferences between the individual desirability of the response variables and their desired characteristics could be considered. The optimal conditions could be different depending on response variables. For example, the MRR (material removal rate) could be the most important parameter in the roughing process to evaluate machinability; on the other hand, surface integrity could be the most important parameter in the finishing process [22]. The optimal conditions of the roughing process will be different from those of the finishing process.

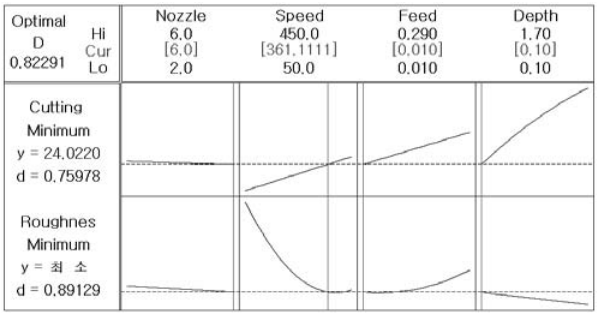
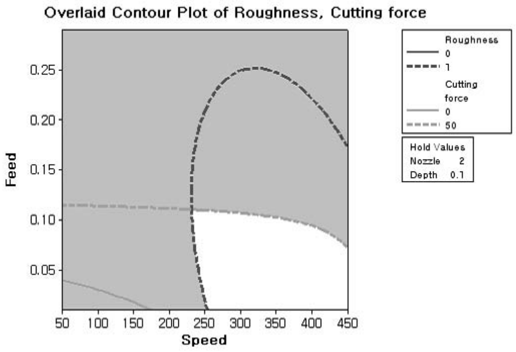


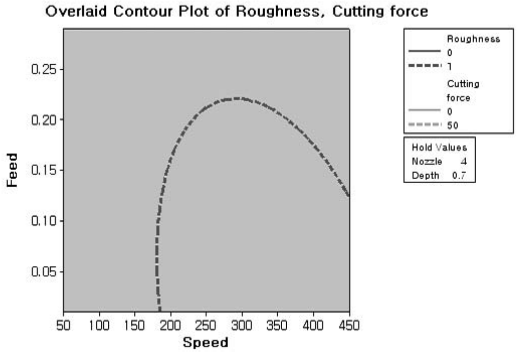
Fig. 6. Effect plots for cutting force and surface roughness in MQL turning.

In this study, the optimal cutting parameters were selected based on combined desirability that satisfies cutting force and surface roughness simultaneously. With the established experimental model, the optimal cutting parameters in the MQL turning, taking into consideration surface roughness and cutting force at the same time, were a nozzle diameter of 6mm, cutting speed of 361m/min, feed rate of 0.01mm/rev, and depth of cut of 0.1mm.

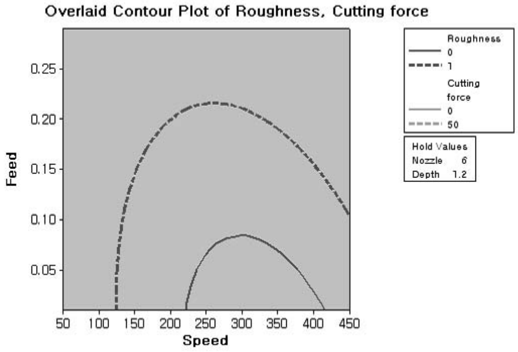
Fig. 7 shows the overlaid plot of the cutting parameter range, which includes cutting force and surface roughness within specific values. The Fig. shows the range of the cutting pa-



(a) Nozzle diameter=2mm, Depth of cut=0.1mm



(b) Nozzle diameter=4mm, Depth of cut=0.7mm



(c) Nozzle diameter=6mm, Depth of cut=1.2mm

Fig. 7. Overlaid plot related to cutting speed, feed rate in MQL turning.

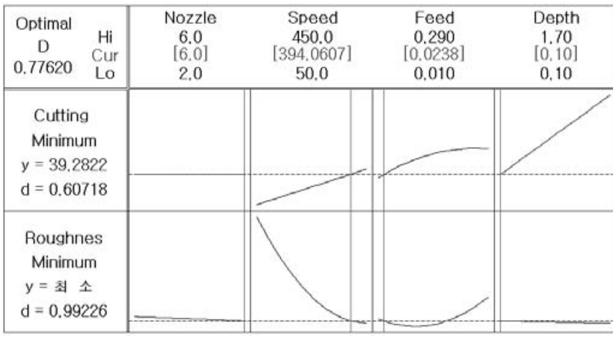


Fig. 8. Effect plots for cutting force and surface roughness in wet turning.

rameters with less than 1 μm of surface roughness and 50N of principal cutting force when the nozzle diameter and depth of cut were fixed at a specific value with cutting speed and feed rate variable. The range that satisfies the conditions can be seen only in Fig. 7(a).

In an ordinary machining process, sometimes the specific cutting parameters need to be fixed because of the characteristics of the machine tool, cutting tool, etc. In this case, selecting a specific level combination of cutting parameters is important because it changes the machinability.

4.3.2 Wet turning

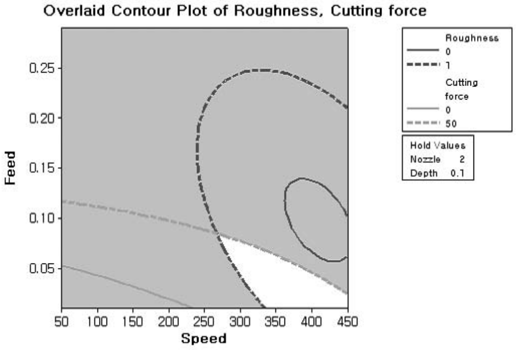
Fig. 8 shows the effects of the individual cutting parameters on surface roughness and cutting force in wet turning.

From the Fig. 8, we can see cutting force was influenced by cutting speed, feed rate, and depth of cut. The better cutting force was achieved with the smaller cutting speed, depth of cut and their relationship was linear. The feed rate had a nonlinear relationship with cutting force and showed a curved surface effect.

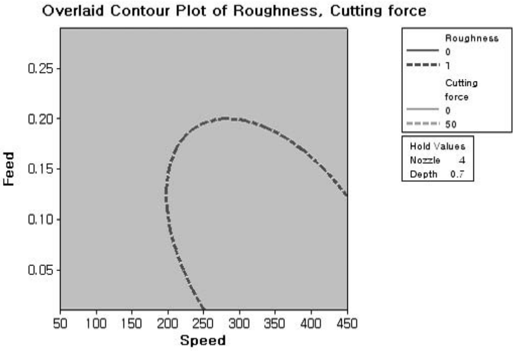
For the surface roughness, the effects of cutting speed, and feed rate were dominant and the effects of nozzle diameter, depth of cut were relatively small. Cutting speed and feed rate had a nonlinear relationship with surface roughness; therefore, there was a saddle point showing the optimal conditions just as in MQL turning.

With the established experimental model, the optimal cutting parameters in the wet turning process were a nozzle diameter of 6mm, cutting speed of 394m/min, feed rate of 0.0238mm/rev, and depth of cut of 0.1mm.

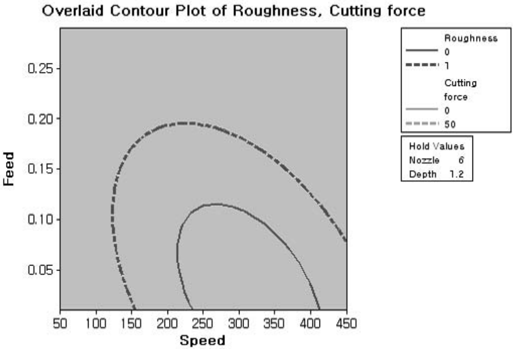
Fig. 9 shows the overlaid plot of the cutting parameter range, which includes cutting force and surface roughness within specific values. It shows the range of the cutting parameters with less than 1 μm of surface roughness and 50N of principle cutting force when the nozzle diameter and depth of cut were fixed in a specific value and cutting speed and feed rate were variable. The range which satisfies the conditions can be seen only in Fig. 9 (a). It was confirmed that using the cutting fluid, as well as MQL, can affect the machinability enormously depending on the level combination of cutting parameters.



(a) Nozzle diameter=2mm, Depth of cut=0.1mm



(b) Nozzle diameter=4mm, Depth of cut=0.7mm



(c) Nozzle diameter=6mm, Depth of cut=1.2mm

Fig. 9. Overlaid plot related to cutting speed, feed rate in wet turning.

Figs. 6 and 8 show all the parameters have the same tendency in the MQL and wet turning operations. For example, a change in surface roughness in response to feed rate showed the same tendency regardless of cooling-lubrication environments. But the parameters showed a different contribution level on the characteristics. For example, the contribution level of depth of cut on the surface roughness was significant in the MQL turning, but in the case of wet turning it was not as significant.

5. Verification experiment

A verification experiment was conducted to confirm the

Table 4. Experimental conditions of verification experiment.

Run order	Nozzle diameter [mm]	Cutting speed [m/min]	Feed rate [mm/rev]	Depth of cut [mm]
1	6	300	0.15	0.3
2	4	370	0.05	0.5
3	6	90	0.10	0.8
4	2	180	0.25	1.5

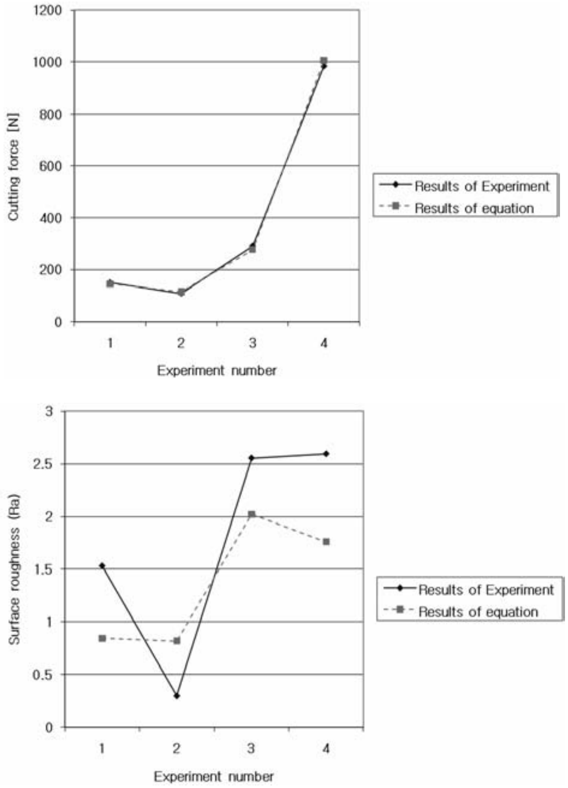


Fig. 10. Comparison plots between verification experiment and suggested equation in MQL turning.

adequacy of the estimated regression model. After choosing four different arbitrary cutting parameters, the prediction value from the equation suggested in this paper and the experimental value were compared through a verification experiment. The cutting conditions are shown in Table 4. All experiments were carried out four times for accurate results.

5.1 MQL turning

Fig. 10 shows the results of verification experiments in the MQL turning. As illustrated in the graph, the cutting force from the experiments matched exactly the prediction value. It confirmed the validity of the experimental equation estimated in the regression model. However, in the case of surface roughness, the experimental values and the prediction values showed a big difference but a similar tendency. This mismatch could be caused by uncontrolled parameters, such as a defect of work materials, lathe vibration, and measuring errors. It is concluded that the proposed equation of surface roughness in this paper is not appropriate for accurate prediction, but could be used only for limited, general tendencies.

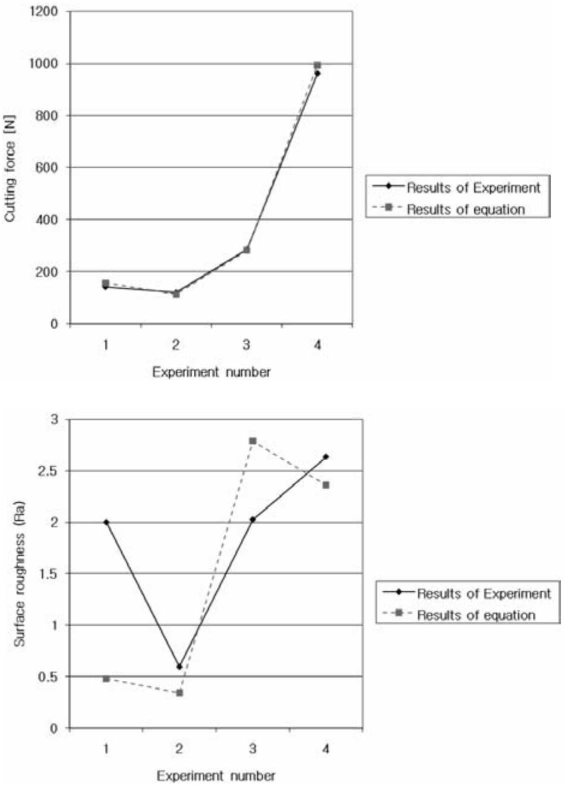


Fig. 11. Comparison plots between verification experiment and suggested equation in wet turning.

5.2 Wet turning

Fig. 11 shows the results of verification experiments in the wet turning. As illustrated in the graph, the cutting force from the experiments matched the predicted value exactly as in the case of MQL turning. This confirmed the validity of the cutting force equation. However, in the case of surface roughness, the experimental values and the predicted values showed a difference in the case of MQL turning. The proposed equation of surface roughness could be used only for prediction of general tendencies.

6. Comparative analysis of MQL and wet turning

Fig. 12 shows the difference of surface roughness according to the cooling-lubrication environments. In most cases, the MQL turning process showed better surface roughness compared with the general wet turning process. In the graph, experiments 7, 9, 12 and 26 show poor surface roughness. In the case of experiment 7, a high feed rate (0.29mm/rev) was thought to cause the extremely poor surface roughness. In the case of experiment 9, a very low cutting speed (50m/min) was thought to cause the poor surface roughness. Those results are in accordance with the already accepted tendencies of general cutting processes. Experiments 12 and 26 had poor surface

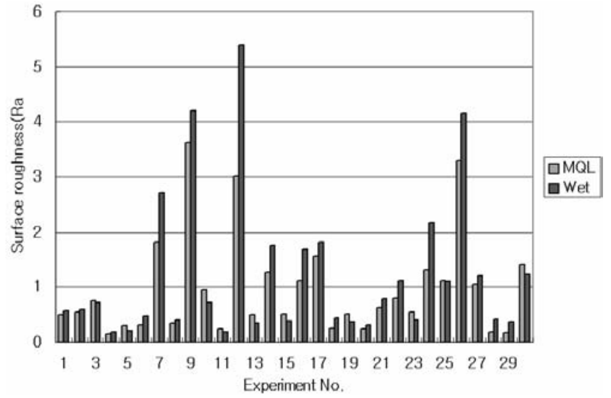


Fig. 12. Comparison plots of surface roughness according to cooling-lubrication environments.

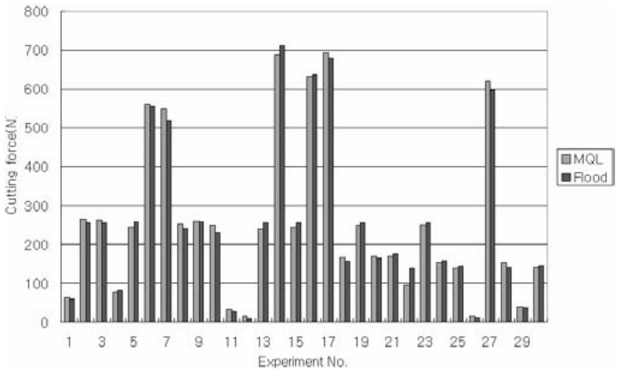


Fig. 13. Comparison plots of cutting force according to cooling-lubrication environments.

roughness with the same cutting conditions, like cutting speed (150m/min), feed rate (0.02mm/rev) and depth of cut (0.2mm). Experiments 14, 16 and 17 had poor surface roughness with the same feed rate (0.2mm/rev) and depth of cut (1.2mm). Those results could have been caused by chatter vibration and the two-factor interaction effects in a specific cutting condition.

Fig. 13 shows the difference of principal cutting force in MQL and wet turning processes. In general, the wet turning operation shows lower cutting force, but the difference is not significant. Experiments 6, 7, 14, 16, 17 and 27 show higher cutting force and their results are different from those of the experiment condition that have poor surface roughness. In the case of higher cutting force, experiments 14, 16, 17 and 27 have the same feed rate (0.2mm/rev) and depth of cut (1.2mm). Experiments 20, 21 and 28 show a lower cutting force with the same depth of cut (1.2mm), but a different feed rate (0.02mm/rev). It was confirmed that cutting force deteriorated with the combination of specific cutting conditions.

Generally, MQL turning has better surface roughness compared with wet turning, but both of them show similar cutting force. Therefore, if we consider only surface roughness and cutting force, switching from wet turning to MQL turning could affect environmental and economical advantages.

7. Conclusions

In this paper, in order to select the optimal cutting parameters and to analyze the effect of cutting parameters on surface roughness and cutting force, experimental equations were suggested. Within the range of cutting parameters used in this study, we were able to draw the following conclusions.

(1) Using fractional factorial design, nozzle diameter, cutting speed, feed rate, and depth of cut were found as the parameters affecting the surface roughness of the MQL turning.

(2) Experimental equations, which can estimate the surface roughness and cutting force in the MQL and wet turning processes of AISI 1045 work material, were suggested with RSM. From the verification experiment, the cutting force equations confirmed the validity in the MQL and wet turning processes, but the surface roughness equations were not appropriate for accurate prediction.

(3) When considering surface roughness and cutting force at the same time in the MQL turning process, the optimal combination of cutting parameters to maximize the machinability was as follows: nozzle diameter of 6mm, cutting velocity of 361m/min, feed rate of 0.01mm/rev, and depth of cut of 0.1mm. In the case of the wet turning process, the optimal combination of cutting parameters consisted of nozzle diameter of 6mm, cutting speed of 394m/min, feed rate of 0.02mm/rev, and depth of cut of 0.1mm.

(4) According to the experiment results, cutting speed and depth of cut showed opposite effects on cutting force and surface roughness. Therefore, cutting conditions should be set under a clear standard because the optimal combination of cutting conditions could be different depending on machinability.

(5) If we consider only surface roughness and cutting force, MQL turning has more advantages than wet turning.

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References

[1] A. E. Diniz and R. Micaroni, Cutting conditions for finish turning process aiming : the use of dry cutting, *International Journal of Machine Tools and Manufacture*, 42 (2002) 899-904.

[2] J. H. Lee and S. J. Lee, Environment-friendly cutting process technology, *Journal of the Korean Society for Precision Engineering,* 18 (2001) 31-36.

[3] J. H. Lee, S. J. Lee, S. W. Lee and H. J. Choi, Characteristics of environment-friendly semi-dry turning, *Journal of the Korean Society for Precision Engineering,* 19 (2002) 221-226.

[4] K. Weinert, I. Inasaki, J. W. Sutherland and T. Wakabayashi, Dry machining and minimum quantity lubrication, *CIRP*

Annals-Manufacturing Technology, 53 (2004) 511-537.

[5] G. Boothroyd and W. A. Knight, *Fundamentals of Machining and Machine Tools*, Tayler & Francis, (2006).

[6] S. H. Yang, Y. M. Lee and Y. S. Kim, Analysis of cutting properties with reference to amount of coolant used in an environment conscious turning process, *KSME International Journal*, 18 (2004) 2182-2189.

[7] S. J. Heo, Environmentally conscious hard turning of cemented carbide materials on the basis of micro-cutting in SEM: stressing four kinds of cemented carbides with PCD tools, *Journal of Mechanical Science and Technology*, 22 (2008) 1383-1390.

[8] A. R. Machado and J. Wallbank, The effect of extremely low lubricant volumes in machining, *International Journal on the Science and Technology of Friction, Lubrication and Wear,* 210 (1997) 76-82.

[9] N. R. Dhar, M. W. Islam, S. Islam and M. A. H. Mithu, The influence of minimum quantity of lubrication on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel, *Journal of Materials Processing Technology* 171 (2006) 93-99.

[10] N. R. Dhar, M. Kamruzzaman and M. Ahmed, Effect of minimum quantity lubrication on tool wear and surface roughness in turning AISI-4340 steel, *Journal of Materials Processing Technology,* 172 (2006) 299-304.

[11] D. U. Braga, A. E. Diniz, G. W. A. Miranda and N. L. Coppini, Using a minimum quantity of lubricant (MQL) and a diamond coated tool in the drilling of aluminum-silicon alloys, *Journal of Materials Processing Technology,* 122 (2002) 127-138.

[12] A. Attanasio, M. Gelfi, C. Giardini and C. Remino, Minimal quantity lubrication in turning: effect on tool wear, *International Journal on the Science and Technology of Friction, Lubrication and Wear,* 260 (2006) 333-338.

[13] F. Itoigawa, T. H. C. Childs, T. Nakamura and W. Belluco, Effects and mechanisms in minimal quantity lubrication machining of an aluminum alloy, *International Journal on the Science and Technology of Friction, Lubrication and Wear*, 260 (2006) 339-344.

[14] Y. K. Hwang, W. J. Chung, J. Y. Jung and C. M. Lee, A study on the improvement of cutting force and surface roughness in MQL turning, *Transactions of the Korean Society of Machine Tool Engineers,* 15 (2006) 83-91.

[15] Y. K. Hwang, W. J. Chung and C. M. Lee, Experimental study of cutting force and surface roughness prediction in MQL turning of Al 6061, *Journal of the Korean Society for Precision Engineering,* 25 (2008) 159-167.

[16] Y. K. Hwang, A study on the improvement of machinability in MQL turning using design of experiments, M.S. Thesis, Changwon National University, (2005).

[17] www.vogelag.com

[18] www.taegutec.co.kr

[19] R. H. Myers and D. C. Montgomery, *Response surface methodology*, A Wiley-Interscience Publication, (2002).

[20] S. H. Park, *Design of Experiments*, Minyoungsa, (2002).

[21] www.minitab.co.kr

[22] M. C. Show, *Metal cutting principles*, Oxford University Press, (2005).

Young-Kug Hwang received his Ph.D. in Mechanical Design and Manufacturing Engineering from Changwon National University in 2010. His research interests include high speed spindle design, variable preload technology of machine tool and environmental conscious machining.

Choon-Man Lee received his Ph.D. degree in Production Engineering from KAIST in 1989. Dr. Lee is currently a Professor at the Department of Mechanical Design and Manufacturing Engineering at Changwon National University. His research interests include plastic working, computer aided manufacturing, machine tool and production engineering.