Universal Journal of Mechanical Engineering 8(2): 97-104, 2020 http://www.hrpub.org
DOI: 10.13189/ujme.2020.080204

Minimization of Temperature in Cutting Zone: A Case Study of Hard Milling of SKD 61 Steel

Quoc Manh Nguyen[1], The-Vinh Do[2,*], Thi-Nguyen Nguyen[3]

[1]Faculty of Mechanical Engineering, Hung Yen University of Technology and Education,
Khoai Chau District, Hung Yen province, Vietnam.
[2]Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen City, Thai Nguyen province, Vietnam.
[3]Center for International Training Cooperation, Thai Nguyen University of Technology, Thai Nguyen City,
Thai Nguyen province, Vietnam.

Received December 17, 2019; Revised February 26, 2020; Accepted March 12, 2020

Abstract The heat generated during metal cutting is a major factor affecting the cutting forces, tool life, and chip formation mode. In this research, the Taguchi method was applied to find the optimal values of cutting parameters in hard milling of SKD 61 steel to minimize cutting temperature under cutting oil and Al_2O_3 nanofluid - MQL condition. The effects of cutting parameters including cutting speed, feed rate and depth of cut were investigated by using an L_9 array of Taguchi method. The signal-to-noise (S/N) ratios and analysis of variance (ANOVA) were applied to analyze the influence of input factors on the cutting temperature. The study result shows that cutting speed is the most influential factor, which gives statistic significant effect on cutting temperature. The speed contributes 52.55 % of total effect under cooling condition of MQL with cutting oil and 53.77 % of total effect under cooling condition of MQL with Al_2O_3 nanofluid. Additionally, the effectiveness in cutting heat reduction of cutting oil - MQL was compared with Al_2O_3 nanofluid - MQL based on experimental measurement of cutting temperature. According to the analysis, the Al_2O_3 nanofluid – MQL is a better option for the cooling conditions during hard milling of SKD 61 steel.

Keywords Cutting Temperature, Nanofluid, MQL, Hard Milling, Taguchi Method, ANOVA

---

1. Introduction

Cutting fluids are employed in the machining process to improve the tribological processes occurring at the interface of the tool and work-piece. Cutting fluids play a role as both lubricants and coolants. The cutting fluid improves the tool life, machined surface of the work-piece and the process as a whole. In addition, it also removes heat and debris generated during cutting. In traditional machining, cutting fluid has been supplied ưith an amount flooding cutting zone. It is named wet machining. The wet machining has several adverse effects such as environmental pollution, damaging the health of operators, increasing production costs related to coolant costs and product cleaning costs [1, 2]. Reducing or even eliminating cutting fluid is a new trend in metal cutting that attracts great interest in manufacturing and research. Dry machining is thought to be capable of removing lubricant during machining with the advancement in cutting tool material technology. Dry machining is a good solution with many advantages especially in environmental and health issues [1, 3-5]. However, high heat generated during dry cutting is a problem that has a negative impact on tool wear and tool life [6, 7]. Minimum quantity lubrication (MQL) is a good solution for both dry cutting and wet cutting. With a minute amount of cutting fluid pulverized in a flow of air directed at the cutting zone during the cutting process, MQL provides with many superior advantages compared to traditional cutting [1, 8, 9]. The MQL in machining not only can obtain the same surface quality as the conventional cutting process with the grinding process under proper parameters but also increases economic efficiency by reducing the lubricant-related costs, increases productivity and eliminates negative environmental impacts [10, 11].

It is well known that heat produced during metal cutting is an important factor affecting the performance of the cutting tool. The thermal phenomena in the cutting process play a key role in controlling tool wear, surface integrity, and machining precision. Many economic and technical issues are directly or indirectly affected by heat during cutting. Shaw et al. believes that excessive heat is a cause of cutting tool wear and damage to the machined surface [12]. Moreover, the heat on the tool face is the main factor affecting the size and stability of the build-up-edge. Therefore, controlling and minimizing cutting heat is the concern of many researchers. In an experimental study of Davoodi, B., and Tazehkandi, A. H. [13], the authors surveyed and optimized the cutting parameters in dry and wet machining conditions aluminum alloy 5083 to eliminate the cutting fluid. A conclusion was given that cutting conditions with the highest cutting speed and lowest undeformed chip thickness result in the least tool tip temperatures in both dry and wet machining. In another study, Raviraj Shetty et al. carried out the experimental investigations of the turning of discontinuously reinforced aluminum composites under three conditions of cooling such as dry, oil-water emulsion, and steam lubricated condition [14]. They concluded that the effect of the lubrication condition is the greatest on the cutting temperature followed by cutting speed. In addition, the cutting temperature increases with cutting speed and feed rate. In an overview study of cutting temperature [15], Da Silva, M. B., and Wallbank, J. reported that the effect of the cutting parameters including the cutting speed, the feed rate, and the depth of cut will lead to an increase in temperature.

In order to enhance the thermal conductivity of cutting fluid, a new technology in MQL machining called nanofluid was introduced by Choi in the use of nanoscale solid particles (less than 100 nm) to add to the cutting fluid in 1995 [16]. The nanoparticle-based cutting fluid has overcome the weakness of conventional cutting fluids which have poor conductivity [17]. The nanoparticles added to the base fluid enhance the thermal conductivity by adding very minute volumetric concentration [18, 19] and, therefore, increase the efficiency of heat exchange [20-22].

The effect of cutting parameters on cutting temperature as well as examining the machining efficiency of nanofluid application has been studied in many studies. However, investigation of the effect of the cutting parameters on the cutting temperature under the condition of Al_2O_3 nanofluid has not been mentioned. Hence, this is the motivation of the authors to investigate the influence of cutting parameters on cutting temperature under Al_2O_3 nanofluid with MQL condition. Al_2O_3 was chosen to be added into cutting oil because of its high performance in reducing cutting force, improving surface roughness, tool wear and chip morphology when compared to conventional cutting fluids. In this study, the Taguchi method was used to find the optimal values of cutting parameters in hard milling of SKD 61 steel to minimize cutting temperature under two cooling conditions such as MQL with cutting oil and MQL with Al_2O_3 nanofluid. The effectiveness in cutting heat reduction of Al_2O_3 nanofluid - MQL was compared to cutting oil - MQL based on experimental measurement of cutting temperature.

2. Experimental procedure

The experiments were carried out on a Victor V-Center-4 vertical machining center. The cutting tool used in the machining test is the ϕ10 TiAlN coated-end mill with four flutes rake angle of 12^o, and helix angle of 35^o. The workpiece is an SKD 61 steel block with dimensions of 150mm × 100mm × 40mm. The workpiece material compositions are shown in Table 1. The hardness of the workpiece is 50HRC. The MQL parameters chosen are 90ml/h for the flow-rate, $3kg/cm^2$ for the air-pressure and CT232 cutting oil for the lubricant. The angle of the MQL nozzle selected is 60^o. The Al_2O_3 nanoparticle size is 20nm. The concentration of nanoparticle in the fluid is 2 wt%. In order to achieve a homogeneous dispersion and stable suspension, the mixture of cutting oil and nano-particles was stirred within 12 hours by using a magnetic stirring device. Measurement data of cutting temperatures is collected by using an infrared camera model IRM_P384A3-20 of Ching Hsing Computer - Tech Ltd. The experiments were carried out at room temperature of about 25^oC. The experiments are described in detail in Table 2. The input factors and levels used during the hard milling of SKD 61 steel are given in Table 3.

Table 1. Chemical compositions of the SKD 61 steel (weight %)

C	Si	Mn	Cr	Mo	V	Ni
0.32 - 0.42	0.80 - 1.20	0.20 - 0.50	4.75 - 5.50	1.10 - 1.75	0.80 - 1.20	0 - 0.30

Table 2. The experimental set-up

Items	**Description**
Milling operation	Slot milling
Machine	Victor V-Center-4
Cutting tool	ϕ10, TiAlN coated, 4 flutes, rake angle of 12°, helix angle of 35°
Workpiece	SKD61 steel, hardness: 50HRC, dimensions: 150mm × 100mm × 40mm
Temperature measurement device	Infrared camera, model IRM_P384A3-20 of Ching Hsing Computer - Tech Ltd.
MQL parameter	Angle of MQL: 600 flow-rate: 90ml/h, air-pressure: 3kg/cm^2, lubricant: CT232 cutting oil
Nano particle	Al_2O_3, size: 20nm, concentration: 2 wt %

Table 3. Input factors and levels

Factors	**Units**	**Levels**		
		1	2	3
Cutting speed (*v*)	m/min	40	60	80
Feed rate (*f*)	mm/tooth	0.01	0.02	0.03
Depth of cut (*d*)	mm	0.2	0.4	0.6

3. Results and Discussions

In experimental research, it is necessary to design the experiment correctly to obtain reliable results. In this study, the Taguchi method was used to design the experiment and analyze the influence of cutting parameters on the temperature in the cutting zone. L_9 orthogonal array was selected to organize the testing procedure. In the Taguchi approach, the signal to noise (S/N) ratio is used to analyze the results. S/N ratio has three types including the bigger is the better, the smaller is the better, and the nominal is the better. Because of minimizing the cutting temperature, the smaller is the better type is selected and calculated by the following formula:

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

Where: y_i is the observed data, n is the number of experiments that are repeated.

The hard milling processes of SKD 61 steel were conducted under two cooling conditions including MQL with cutting oil and MQL with Al_2O_3 nanofluid. The results of the cutting temperature and S/N ratio given by Minitab 17 software are shown in Table 4. In Table 4, the input factors include the cutting velocity (*v*), the feed rate (*f*), and depth of cut (*d*). T_1 and T_2 are the cutting temperatures measured under two cooling conditions of MQL with cutting oil and MQL with Al_2O_3 nanofluid, respectively. The measured temperature values range from 35.1 °C to 59.1°C for MQL with Al_2O_3 nanofluid condition and from 38.3 °C to 66.1 °C for MQL with cutting oil condition.

Table 4. The results of the cutting temperature and S/N ratio

No.	**Cutting parameters**			**MQL with cutting oil**		**MQL with Al_2O_3 nanofluid**	
	v **(m/min)**	***f*** **(mm/tooth)**	***d*** **(mm)**	**Cutting temp. T_1 (°C)**	**Computed S/N ratio**	**Cutting temp. T_2 (°C)**	**Computed S/N ratio**
1	40	0.01	0.2	38.3	-31.6640	35.1	-30.9061
2	40	0.02	0.4	42.1	-32.4856	40.3	-32.1061
3	40	0.03	0.6	51.9	-34.3033	49.3	-33.8569
4	60	0.01	0.4	48.8	-33.7684	46.6	-33.3677
5	60	0.02	0.6	58.1	-35.2835	54.4	-34.7120
6	60	0.03	0.2	45.2	-33.1028	44.2	-32.9084
7	80	0.01	0.6	66.1	-36.4040	59.1	-35.4317
8	80	0.02	0.2	51.2	-34.1854	50.2	-34.0141
9	80	0.03	0.4	59.1	-35.4317	56.7	-35.0717

3.1. Minimizing of Cutting Temperature under MQL with Cutting Oil Condition

The S/N response given by the Taguchi method is applied to determine the most effective one of input factors on the response factor. The highest values of S/N show the optimum level of each input factor. The analysis of the S/N response is depicted in Figure 1. As shown in Figure 1, the S/N response analysis shows that, under MQL with cutting oil, the optimal condition of cutting parameters to minimize the temperature is the cutting speed of 40 m/min, the feed rate of 0.01 mm/tooth, and the depth of cut of 0.2 mm. This optimal machining mode corresponds to experiment No. 1 for T_1 shown in Table 4. The result of the cutting temperature in the experiment No.1 is 38.3 ^{o}C, being the lowest value of T_1. It proves the reliability of the analytical results.

The ANOVA results for the effect levels of the input factors on cutting temperature are shown in Table 5. As shown in Table 5, the cutting velocity is the most influential factor on the cutting temperature followed by the depth of cut under the cooling condition of MQL with cutting oil. The percentage contribution to the total effect of these factors is 52.55% and 46.2 %, respectively. The effect of the speed and the depth of cut on the temperature have statistical significance with a P-value less than 0.05. On the other hand, the effect of the feed rate on the temperature is negligible with a 1.1% contribution. With a P-value greater than 0.05, the effect of feed rate has no significant difference.

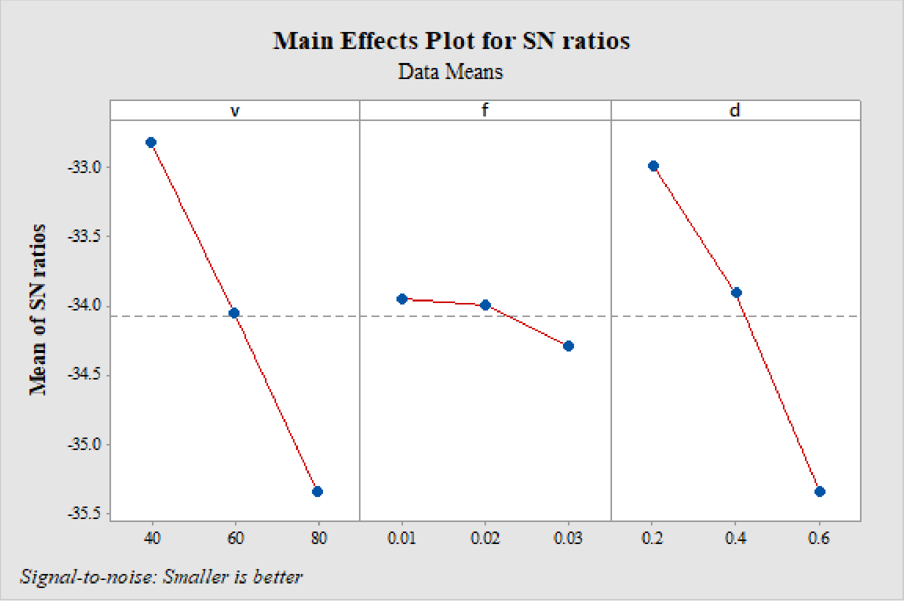


Figure 1. The analysis of S/N response for T_1

Table 5. ANOVA for the cutting temperature T_1

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PC (%)
v	2	9.5478	9.54782	4.77391	366.29	0.003[a]	52.55
f	2	0.1997	0.19968	0.09984	7.66	0.115	1.10
d	2	8.3945	8.39454	4.19727	322.04	0.003[a]	46.20
Residual Error	2	0.0261	0.02607	0.01303	-	-	-
Total	8	18.1681	-	-	-	-	-

R-Sq = 99.9% R-Sq(adj) = 99.4%

[a] significant

3.2. Minimizing of Cutting Temperature under MQL with Al_2O_3 Nanofluid Condition

Figure 2 depicts the analysis of S/N response for the cutting temperature under MQL with Al_2O_3 nanofluid condition. Similar to the condition of MQL with cutting oil, when applying MQL with Al_2O_3 nanofluid condition, the optimal condition of cutting parameters to minimize the temperature is the cutting speed of 40 m/min, the feed rate of 0.01 mm/tooth, and the depth of cut of 0.2 mm. This optimal machining mode corresponds to experiment No. 1 for T_2 shown in Table 4. The result of the cutting temperature in the experiment No.1 is 35.1 ^{o}C, being the lowest value of T_2. It proves the reliability of the analytical results.

Table 6 shows the ANOVA results for the effect levels of the input factors on cutting temperature under MQL with Al_2O_3 nanofluid condition. According to the ANOVA results, the most important factor influencing the temperature is recorded to be the cutting speed with 53.77% contribution. Following the cutting speed is the depth of cut with a 35.11 % contribution. The effect of these factors has statistical significance with a P-value of less than 0.05. The effect of the feed rate on the temperature is negligible and has no significant difference with a 4.17% contribution and P-value greater 0.05.

3.3. Effect of the Cutting Parameters on the Temperature

The influence of the cutting parameters such as the speed, the feed rate, and the depth of cut on the temperature in the cutting zone can be noted by the analysis of Figure 3. Clearly, under both cooling conditions, the temperature raised by the increase of all cutting parameters. This is in agreement with the results of previous studies such as those of M. Hirao and of M. Mia and N. R. Dhar [23, 24]. As shown in Figure 3, the temperature increases sharply by an increase in the cutting speed. It is explained that the heat generated in the cutting zone does not have enough time to spread to the surrounding environment with the increase of cutting speed [12, 24]. The increase in the depth of cut also causes a marked increase in the temperature. However, the change of cutting temperature is slight with the increase in feed rate. Figure 3 confirms that the cutting spees, followed by the depth of cut, has the greatest effect on the cutting temperature. The effect of feed rate is negligible.

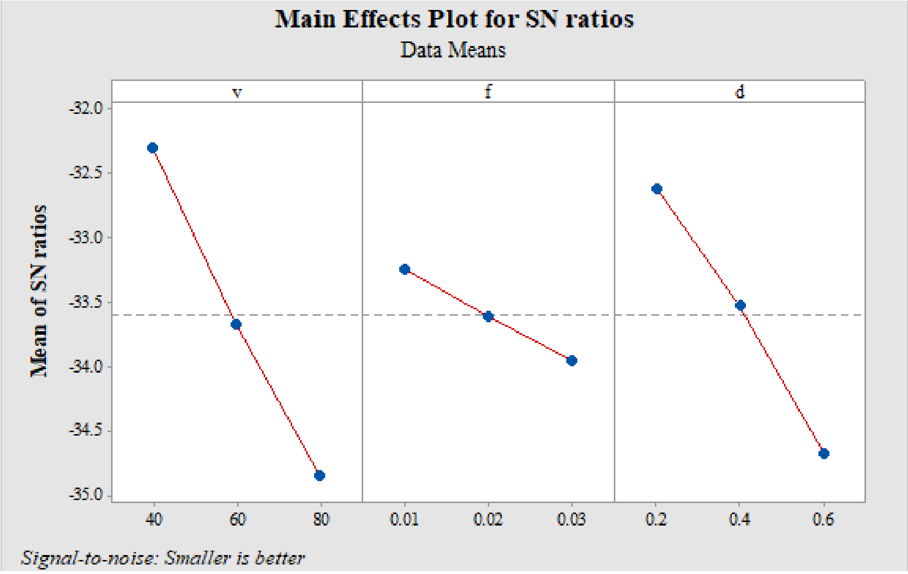


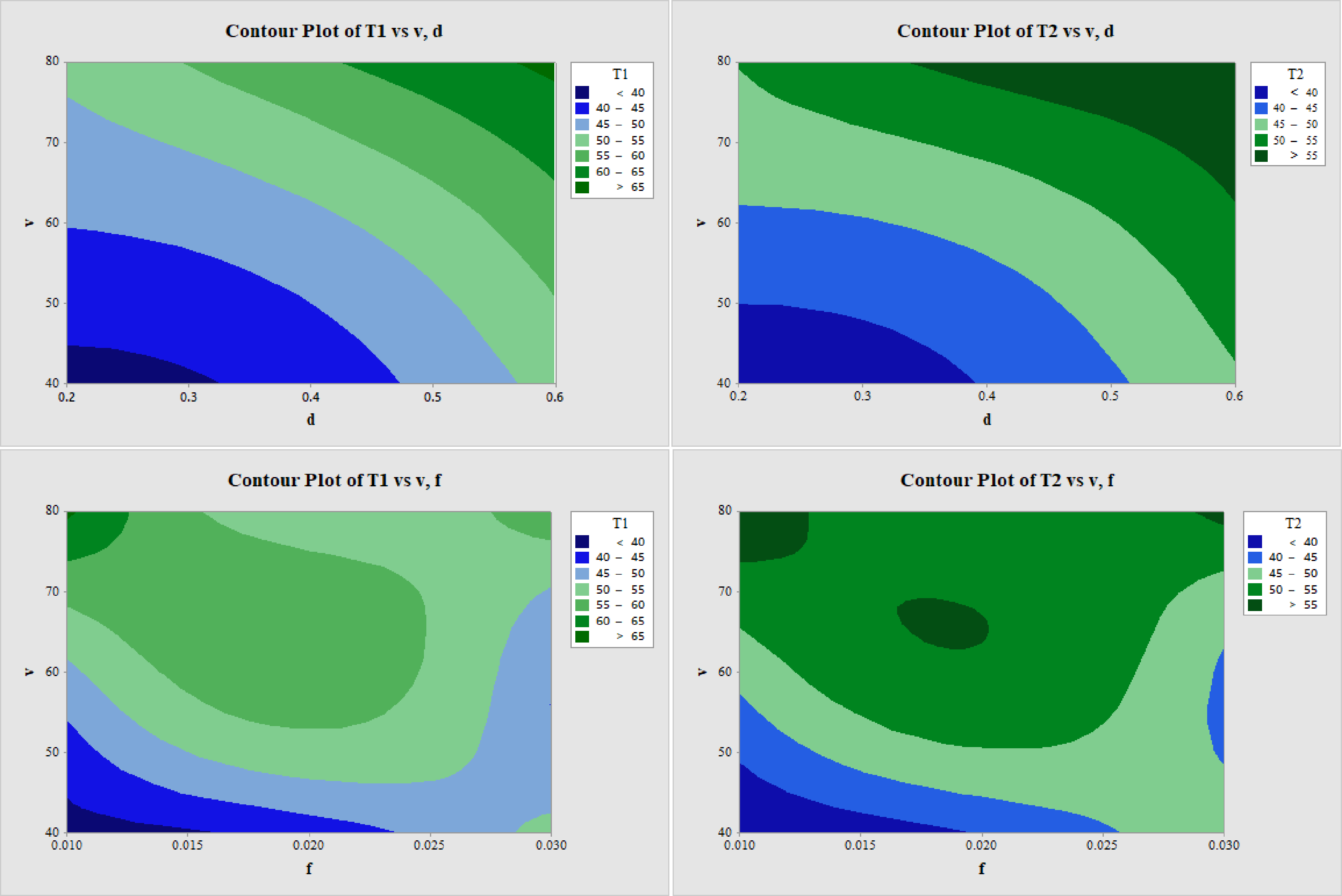
Figure 2. The analysis of S/N response of T_2

Table 6. ANOVA for the cutting temperature T_2

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PC%
v	2	9.7687	9.7687	4.88437	88.93	0.011[a]	53.77
f	2	0.7580	0.7580	0.37900	6.90	0.127	4.17
d	2	6.3792	6.3792	3.18961	58.08	0.017[a]	35.11
Residual Error	2	0.1098	0.1098	0.05492	-	-	-
Total	8	17.0158	-	-	-	-	-

R-Sq = 99.4% R-Sq(adj) = 97.4%

[a] significant



Contour Plot of T1 vs v, d

Contour Plot of T2 vs v, d

Contour Plot of T1 vs v, f

Contour Plot of T2 vs v, f

Figure 3. Contour plot of temperature versus cutting parameters

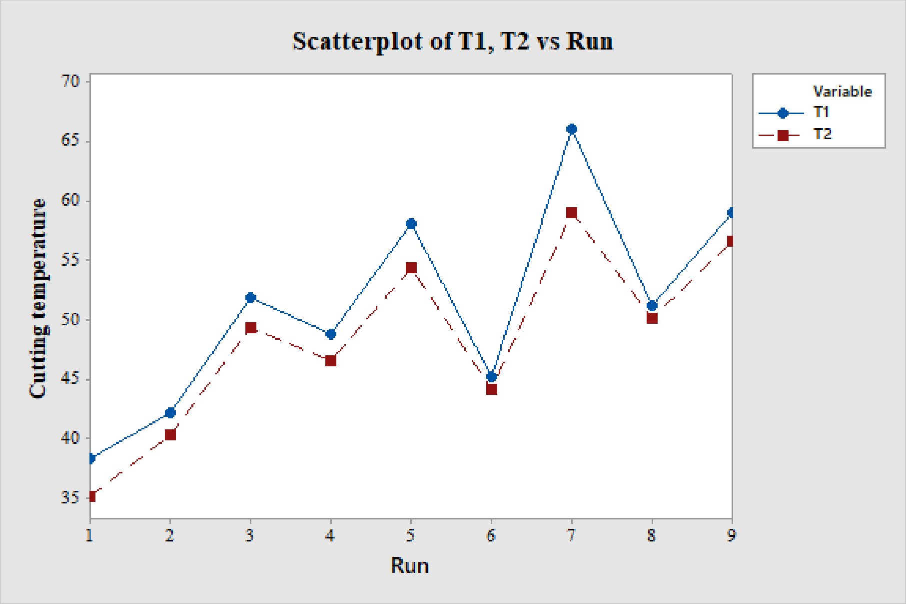


Figure 4. Comparison of effectiveness in cutting temperature reduction of two cooling conditions

3.4. Comparison of Effectiveness in Cutting Temperature Reduction of Two Cooling Conditions

The effectiveness in cutting temperature reduction of Al_2O_3 nanofluid - MQL was compared to cutting oil - MQL based on experimental measurement of cutting temperature as shown in Figure 4. It can be easily observed that the cutting temperature when using the cooling condition of Al_2O_3 nanofluid - MQL is lower than that of cutting oil - MQL. It can be explained that the nanoparticles added to the base fluid enhance the thermal conductivity by adding very minute volumetric concentration and, therefore, increase the efficiency of heat exchange. Therefore, the Al_2O_3 nanofluid – MQL is a better option for the cooling conditions during hard milling of SKD 61 steel.

4. Conclusions

In this study, the Taguchi method was used to find the optimal values of cutting parameters in hard milling of SKD 61 steel to minimize cutting temperature under two cooling conditions such as MQL with cutting oil and MQL with Al_2O_3 nanofluid. The results obtained in this context are listed as follows:

- Under both cutting conditions, lower cutting-speed, lower feed-rate, lower depth-of-cut, and lower hardness, it resulted in minimum cutting temperature. The optimal cutting parameters for minimizing the temperature in cutting zone are the cutting speed of 40 m/min, the feed rate of 0.01 mm/tooth, and the depth of cut of 0.2 mm.
- In both cooling conditions, the cutting speed is the most influential factor on the cutting temperature followed by the depth of cut. The speed contributes 52.55 % of total effect under MQL with cutting oil and 53.77 % of total effect under MQL with Al_2O_3 nanofluid. The depth of cut contributes 46.20 % of total effect under MQL with cutting oil and 35.11 % of total effect under MQL with Al_2O_3 nanofluid.
- The cutting temperature when using the cooling condition of Al_2O_3 nanofluid - MQL is lower than that of cutting oil – MQL, the Al_2O_3 nanofluid – MQL is a better option for the cooling conditions during hard milling of SKD 61 steel.

Acknowledgements

The authors wish to thank Thai Nguyen University of Technology. This work was supported by Thai Nguyen University of Technology.

REFERENCES

[1] T.-V. Do and Q.-C. Hsu, "Optimization of minimum quantity lubricant conditions and cutting parameters in hard milling of AISI H13 steel," Applied Sciences, vol. 6, p. 83, 2016.

[2] J. Buongiorno, "Convective transport in nanofluids," Journal of heat transfer, vol. 128, pp. 240-250, 2006.

[3] T.-V. Do and N.-A.-V. Le, "Optimization of Surface Roughness and Cutting Force in MQL Hard-Milling of AISI H13 Steel," in Advances in Engineering Research and Application: Proceedings of the International Conference, ICERA 2018, 2019, pp. 448-454.

[4] T.-V. Do, N.-C. Vu, and Q.-M. Nguyen, "Optimization of

cooling conditions and cutting parameters during hard milling of AISI H13 steel by using Taguchi method," in 2018 IEEE International Conference on Advanced Manufacturing (ICAM), 2018, pp. 396-398.

[5] A. Devillez, G. Le Coz, S. Dominiak, and D. Dudzinski, "Dry machining of Inconel 718, workpiece surface integrity," Journal of Materials Processing Technology, vol. 211, pp. 1590-1598, 2011.

[6] B. Denkena, J. Köhler, and B. Bergmann, "Development of cutting edge geometries for hard milling operations," CIRP Journal of Manufacturing Science and Technology, vol. 8, pp. 43-52, 2015.

[7] L. Qian and M. R. Hossan, "Effect on cutting force in turning hardened tool steels with cubic boron nitride inserts," Journal of Materials Processing Technology, vol. 191, pp. 274-278, 2007.

[8] K.-H. Park, G.-D. Yang, M. Suhaimi, D. Y. Lee, T.-G. Kim, D.-W. Kim, et al., "The effect of cryogenic cooling and minimum quantity lubrication on end milling of titanium alloy Ti-6Al-4V," Journal of Mechanical Science and Technology, vol. 29, pp. 5121-5126, 2015.

[9] H. Hassanpour, M. H. Sadeghi, A. Rasti, and S. Shajari, "Investigation of surface roughness, microhardness and white layer thickness in hard milling of AISI 4340 using minimum quantity lubrication," Journal of Cleaner Production, vol. 120, pp. 124-134, 2016.

[10] Q. An, C. Wang, J. Xu, P. Liu, and M. Chen, "Experimental investigation on hard milling of high strength steel using PVD-AlTiN coated cemented carbide tool," International Journal of Refractory Metals and Hard Materials, vol. 43, pp. 94-101, 2014.

[11] Y. Liao, H. Lin, and Y. Chen, "Feasibility study of the minimum quantity lubrication in high-speed end milling of NAK80 hardened steel by coated carbide tool," International Journal of Machine Tools and Manufacture, vol. 47, pp. 1667-1676, 2007.

[12] M. C. Shaw and J. Cookson, Metal cutting principles vol. 2: Oxford university press New York, 2005.

[13] B. Davoodi and A. H. Tazehkandi, "Experimental investigation and optimization of cutting parameters in dry and wet machining of aluminum alloy 5083 in order to remove cutting fluid," Journal of Cleaner Production, vol. 68, pp. 234-242, 2014.

[14] R. Shetty, R. Pai, and S. S. Rao, "Experimental Studies on Turning of Discontinuously Reinforced Aluminium Composites under Dry, OilWater Emulsion and Steam Lubricated Conditions Using TAGUCHIâ s Technique," Gazi University Journal of Science, vol. 22, pp. 21-32, 2009.

[15] M. B. da Silva and J. Wallbank, "Cutting temperature: prediction and measurement methods—a review," Journal of materials processing technology, vol. 88, pp. 195-202, 1999.

[16] S. Choi and A. Jeffrey, "Eastman, enhancing thermal conductivity of fluids with nanoparticles," Developments and Applications of Non-Newtonian Flows, vol. 231, pp. 99-105, 1995.

[17] N. A. C. Sidik, S. Samion, J. Ghaderian, and M. N. A. W. M. Yazid, "Recent progress on the application of nanofluids in minimum quantity lubrication machining: A review," International Journal of Heat and Mass Transfer, vol. 108, pp. 79-89, 2017.

[18] A. Moghadassi, S. M. Hosseini, D. Henneke, and A. Elkamel, "A model of nanofluids effective thermal conductivity based on dimensionless groups," Journal of Thermal Analysis and Calorimetry, vol. 96, pp. 81-84, 2009.

[19] W. Yu, H. Xie, L. Chen, and Y. Li, "Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid," Thermochimica Acta, vol. 491, pp. 92-96, 2009.

[20] B. Li, C. Li, Y. Zhang, Y. Wang, D. Jia, M. Yang, et al., "Heat transfer performance of MQL grinding with different nanofluids for Ni-based alloys using vegetable oil," Journal of Cleaner Production, vol. 154, pp. 1-11, 2017.

[21] Y. Xuan and Q. Li, "Heat transfer enhancement of nanofluids," International Journal of heat and fluid flow, vol. 21, pp. 58-64, 2000.

[22] L. Godson, B. Raja, D. M. Lal, and S. Wongwises, "Enhancement of heat transfer using nanofluids—an overview," Renewable and sustainable energy reviews, vol. 14, pp. 629-641, 2010.

[23] M. Hirao, "Determining temperature distribution on flank face of cutting tool," Journal of Materials Shaping Technology, vol. 6, pp. 143-148, 1989.

[24] M. Mia and N. R. Dhar, "Optimization of surface roughness and cutting temperature in high-pressure coolant-assisted hard turning using Taguchi method," The International Journal of Advanced Manufacturing Technology, vol. 88, pp. 739-753, 2017.