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On Investigation of Effects of Mos$_2$ Nanofluid MQCL Condtion on the Hard Milling Performance of SKD 11 Tool Steel

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Abstract
Hard machining technology has attracted much attention in the field of metal cutting and has been applied more widely in production practice, in which hard milling exhibits the outstanding productivity while ensuring high dimensional accuracy and good machined surface quality. The main objective of this paper is to investigate the influence of input parameters (cutting speed, nanoparticle concentration, and feed rate) on machined surface roughness R_a in hard milling of SKD 11 tool steel under Minimum Quantity Cooling Lubrication (MQCL) condition. Box-Behnken experimental planning design was used to build up the experimental matrix. The obtained results indicated that feed rate was the factor having the most influence while the MoS_2 nanoparticle concentration and cutting speed also cause the significant effects. Moreover, the proper values of these input variables were provided to be the useful technical guides achieve the better machined surface roughness in the further studies and machining practice.

Keywords: Hard Milling, MQCL, Nanofluid, Cutting Speed, Feed Rate, Surface Roughness

1. Introduction

In manufacturing industry, milling is a machining process used to remove material from a workpiece. This process uses rotary cutters with multiple cutting edges and is commonly performed on the milling machines [1]. For technological capacity, milling can produce a wide range of surface finishes and is used for both roughing and finishing operations [2]. Recently, hard milling technology was developed and has been widely applied in the production practice [3]. The use of hard milling to directly cut the high-hardness materials has brought new technological solutions to replace or support traditional solutions such as grinding and Electrical Discharge Machining (EDM) [4]. In addition, this method provides superior productivity while still ensuring high dimensional accuracy and good surface quality.

Up to now, the cutting oils have been playing the key roles in lubricating and cooling the cutting zone, but the disposal of used cutting oil is one of the main causes of environmental pollution [5], while the treatment cost is very high. At the same time, the strict environmental regulations such as ISO 14000 and Green Round are setting new standards and requirements towards the sustainable production [6]. Accordingly, the reduction of cutting oil consumption is the growing concern and the application of the biodegradable cutting fluids is promoted. The application of cutting oil under wet condition for the hard milling process is difficult. Because the cutting process is not continuous with high cutting force and cutting temperature, it is easy to cause thermal shock, leading to chipping and breakage phenomena on the cutting tools. This seriously affects the quality of the machined surface, tool life and manufacturing cost [3]. Hence, hard milling under dry condition is considered as the simplest environmentally friendly way and has been applied in practice. Nevertheless, the enormous amount of cutting heat combined with the high cutting forces is the huge challenge, which accelerates the tool wear and shortens tool life [7]. Accordingly, the cutting tool materials are needed to have the excellent hardness, heat resistance, and wear resistance. The commonly used cutting tool materials include Cubic Boron Nitride (CBN), ceramics, coated carbide tools, and so on [8]. Besides, the selection of the cutting parameters also plays a crucial role, determining the efficiency of the cutting process [9].

In order to further improve the efficiency of the hard milling process, there is a need to develop the novel cooling and lubricating techniques. Minimum Quantity Cooling Lubrication (MQCL) using nanofluids has been proposed and developed in recent years [10], which not only provides the superior cooling lubrication effects but also was proven to be suitable for hard milling. However, the studies on this technique are limited, so the main objective of this paper is to study the effects of MoS_2 nanofluid MQCL environment on hard milling of SKD 11 tool steel (60-62HRC).

2. Methodology

2.1 Experimental design

Box-Behnken experimental design with the help of Minitab 19.0 software is utilized for three input parameters including cutting speed, nanoparticle concentration, and feed rate (Table 1).

Table 1: Box-Behnken experimental design with the input variables and their levels.

Input variables	Low level	High level	Response variables
Cutting speed, V (m/min)	110	140	Surface roughness R_a (μm)
Nanoparticle concentration, NC (%)	0.1	0.3	
Feed rate, f (mm/min)	0.01	0.03	

2.2 Experimental devices

The hard milling experiments were implemented on Mazak vertical center smart 530C (Japan), and the experimental setup is shown in Figure 1. The chemical composition of SKD 11 tool steel is shown in Table 2. The coated carbide inserts with the designation of APMT 1604 PDTR LT30 was used (Figure 2). The MoS_2 nanoparticles were suspended in water-based emulsion 5% to form the nanofluid, which was used as the cutting fluid for MQCL system. The depth of cut was fixed at 0.12 mm. Surftest SJ-210 Mitutoyo (Japan) was used for surface roughness measurement, and the values of surface roughness were measured 3 times after each cutting trial and taken by the average value.

Table 2: Chemical composition of SKD 11 tool steel

Chemical Composition (%)										
C	Si	Mn	Ni	Cr	Mo	W	V	Cu	P	S
1.4–1.6	0.4	0.6	0.5	11.0–13.0	0.8–1.2	0.2–0.5	≤0.25	≤0.25	≤0.03	≤0.03

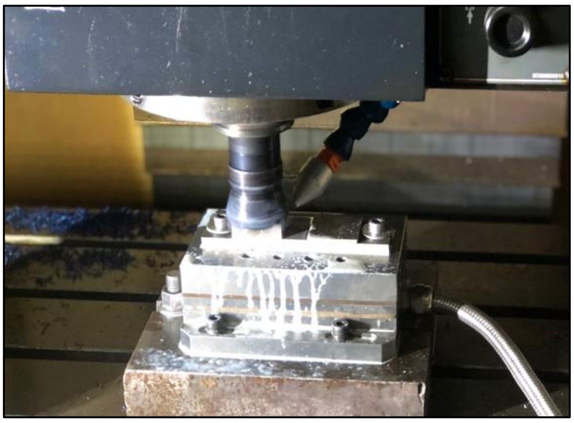

Fig 1: Experimental set up

Fig 2: Milling head and carbide inserts used in the hard milling experiment

3. Results and Discussion

The cutting trials were conducted by following the experimental run order, and the surface roughness values were measured and reported after each trial. The Pareto chart of the input parameters exhibits the effects of the input parameters and their interaction effects on the surface roughness (Figure 3).

The ANOVA analysis with 95% confidence level is done for surface roughness R_a with R_2 equal to 98.81%, proving that the experimental data fit well with the experimental design model. Table 3 shows the results of ANOVA analysis. It can be seen that in the last columns of Table 3, most of the input variables have the p-values smaller than the significance level (0.05). It means that the cutting speed, nanoparticle concentration, and feed rate have the significant influences on the response parameter R_a. The regression models for Ra is given in Equation 1.

Ra (µm)= -0.465 + 0.00905 V + 0.072 NC + 7.55 f - 0.000035 V*V - 0.429 NC*NC + 89.6 f*f + 0.00017 V*NC - 0.0667 V*f + 1.00 NC*f (1)

Table 3: Results of ANOVA analysis of surface roughness R_a

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.010000	0.001111	45.95	0.000
Linear	3	0.008961	0.002987	123.52	0.000
V (m/min)	1	0.001485	0.001485	61.41	0.001
NC (%)	1	0.000276	0.000276	11.42	0.020
f (mm/min)	1	0.007200	0.007200	297.73	0.000
Square	3	0.000635	0.000212	8.75	0.020
V*V	1	0.000224	0.000224	9.27	0.029
NC*NC	1	0.000068	0.000068	2.81	0.154
f *f	1	0.000296	0.000296	12.25	0.017
2-Way Interaction	3	0.000404	0.000135	5.57	0.047
V*NC	1	0.000000	0.000000	0.01	0.923
V*f	1	0.000400	0.000400	16.54	0.010
NC*f	1	0.000004	0.000004	0.17	0.701
Error	5	0.000121	0.000024		
Lack-of-Fit	3	0.000112	0.000037	8.63	0.106
Pure Error	2	0.000009	0.000004		
Total	14	0.010121			

In Figure 3, it was noticeable that feed rate causes the strongest influence on the surface roughness R_a, followed by cutting speed and then the nanoparticle concentration. The interaction effect of feed rate and cutting speed as well as the quadratic interaction effects of feed rate and cutting speed also has the significant influences.

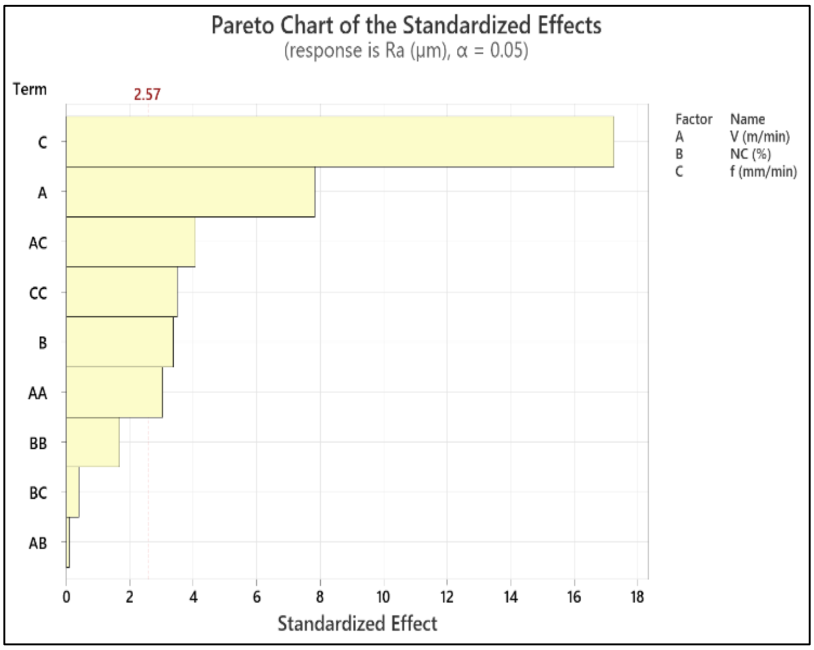

Fig 3: Pareto chart of the input parameters on surface roughness R_a

Figure 4 illustrates the main effect of each input factor on the surface roughness R_a. The values of surface roughness R_a rapidly go up with the increase of feed rate from 0.01mm/min to 0.03mm/min. In contrast, R_a values decrease when the cutting speed and MoS_2 nanoparticle concentration rise. Hence, the suitable values of the input variables are the cutting speed V=140m/min, MoS_2 nanoparticle concentration NC=0.3%, and feed rate f=0.01mm/min. In figure 5, the interaction effects between the feed rate and cutting speed are more significant than the other ones. The interaction influence of nanoparticle concentration and feed rate is less influence.

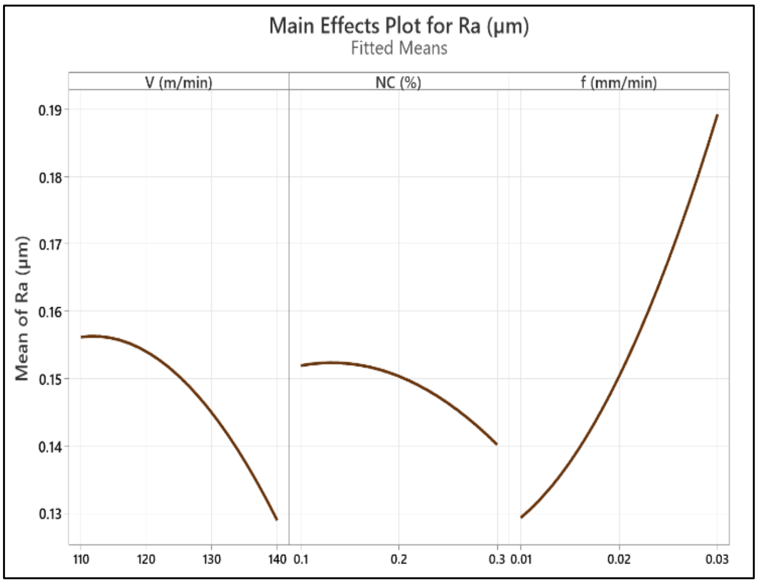

Fig 4: Main effects of the input parameters on surface roughness R_a

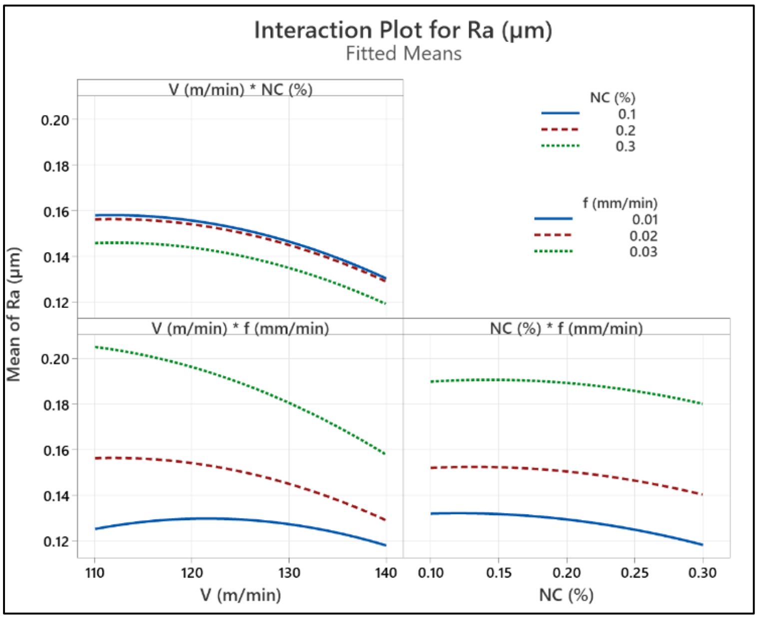

Fig 5: Interaction effects of the input parameters on surface roughness R

4. Conclusion

In this article, the hard milling experiments under MQCL environment using MoS_2 nanofluid were successfully conducted to study the effect of the cutting speed, nanoparticle concentration, and feed rate on surface roughness R_a. Based on the obtained results, MoS_2 nanofluid MQCL technique provides the superior cooling and lubricating effects, thereby improving the hard milling performance and machinability of carbide tools. Box-Behnken experimental planning design was used to investigate the impacts and effect trend of the investigated variables. Among the three input variables, feed rate causes the strongest impact on R_a, followed by cutting speed and nanoparticle concentration. Moreover, the interaction effect of feed rate and cutting speed as well as the quadratic interaction effects of feed rate and cutting speed also has the significant influences. The cutting speed V=140m/min, MoS_2 nanoparticle concentration NC=0.3%, and feed rate f=0.01mm/min are specified and selected to achieve the smaller surface roughness R_a.

5. Acknowledgments

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