Optimization of Surface Roughness and Cutting Force in MQL Hard-Milling of AISI H13 Steel

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Abstract. Minimum quantity lubrication (MQL) has been applied successfully to hard milling as an alternative to flood coolant processing and dry cutting. The objective of this research is to optimize process parameters to find the minimal values of surface roughness and cutting force during MQL hard milling of AISI H13 steel with coated carbide (TiAlN) cutting tool. The characteristics of the cutting force and the surface roughness obtained under MQL condition were experimentally investigated. The experiments were conducted using the L27 orthogonal array of Taguchi's experimental design technique. The response surface methodology (RSM) and analysis of variance (ANOVA) were employed to analyze the influence of cutting parameters (i.e., cutting speed, feed rate, depth-of-cut and hardness of workpiece) on the cutting force and the surface roughness. The statistical models to predict cutting force and surface roughness under MQL condition were established.

Keywords: MQL · Hard milling · Cutting force · Roughness
RSM · ANOVA

1 Introduction

Many studies have addressed the question "*Why perform MQL cutting?*". According to Diniz et al. [1], MQL is an acronym used to describe a procedure in which a very small amount of lubricant (<50 ml/h) is pulverized in a flow of air directed at the cutting zone during milling. MQL has been widely applied in the machining processes (i.e., milling, turning and drilling) due to efficiency and environmental issues. The effectiveness of MQL has already been demonstrated with the improvement of surface roughness [2–5], reduction of tool wear, enhancement of tool life, a decrease in cutting temperature, and a reduction in lubricant-related costs [2, 3, 5–10]. Many studies proved for the benefits of using MQL in machining in comparison with dry cutting and wet cutting methods. In the research of Dhar et al. [3], the effect of MQL on tool wear and surface roughness in turning AISI-4340 steel was significant. There was a noticeable reduction in tool wear and surface roughness by MQL due to a reduction of temperature in the cutting zone and a favorable change in the chip–tool and work–tool interaction. In comparison with wet and dry cutting [5], MQL effects using vegetable oil-based cutting fluid were

H. Fujita et al. (Eds.): ICERA 2018, LNNS 63, pp. 448–454, 2019.
https://doi.org/10.1007/978-3-030-04792-4_58

presented. The significant contributions of MQL to turning AISI 9310 alloy steel were a reduction of cutting temperature, a decrease in tool wear, and an improvement of surface roughness. Similarly, in research of Dhar et al. [6] reduction of cutting temperature was presented in turning AISI-1040 steel by employing MQL. In the milling process, the effectiveness of MQL was also demonstrated in many other studies. The tool life enhanced by an application of MQL was expressed in high-speed end milling of AISI D2 cold-worked die steel with 62 HRC in a study by Kang et al. [7], and in the research by Iqbal et al. [8]. In a study by Inconel 718 steel milling [11], Thamizhmanii et al. concluded that surface roughness obtained by using MQL is lower than that obtained by dry cutting. The tool life was improved by 43.75% by MQL rather than by dry cutting. Rahman et al. [12] concluded that the surface roughness obtained by MQL is equivalent to what was obtained through wet cooling means. The difference in cutting force between that of flood cooling and MQL was considered to be insignificant.

The application of MQL in hard-milling of AISI H13 steel has not been adequately studied to date. Consequently, the author continued to respond to the question of "*Why use MQL cutting*?". In this research, the values of surface roughness and cutting force components were collected in a series of meticulous experiments. The experimental design was performed by using the L27 orthogonal array of Taguchi's experimental design technique. The second-order models for prediction of surface roughness and cutting force under MQL were established by means of RSM. The results expressed optimal values of cutting parameters to achieve minimal values of surface roughness and cutting force.

2 Experimental Procedure

The L27 orthogonal array of Taguchi's experimental design technique was used to design the experiment. The cutting parameters are cutting-speed (v), feed-rate (f), depth-of-cut (d) and hardness-of-workpiece (h). Each parameter includes three levels (1, 2, and 3). The cutting parameters with three levels are shown in Table 1.

Table 1. Cutting parameters with levels

Levels	Cutting parameters			
	v (m/min)	F (mm/tooth)	d (mm)	h (HRC)
1	40	0.01	0.2	40
2	55	0.02	0.4	45
3	70	0.03	0.6	50

A series of meticulous experiments related to the hard-milling of AISI H13 steel was conducted under MQL condition. The cutting tool used is Φ10 TiAlN coated end mill. MQL parameters applied were water soluble oil used for the lubricant, 50 ml/h for the flow rate, and 3 kg/cm^2 for the pressure [13]. In order to reduce the possibility for experimental errors to occur, each experiment was repeated five times.

3 Results and Discussion

Table 2 shows the results of the experiment for surface roughness and cutting force components.

Table 2. Experimental results for surface roughness and cutting force components.

No.	v	f	d	h	Ra (μm)	Fx (N)	Fy (N)	Fz (N)
1	40	0.01	0.2	40	0.151	46.2	40.4	6
2	40	0.01	0.4	45	0.202	136.5	86.7	15.6
3	40	0.01	0.6	50	0.285	160.5	187.9	24.5
4	40	0.02	0.2	45	0.181	84.1	70.7	10.8
5	40	0.02	0.4	50	0.221	170.3	182.4	24.8
6	40	0.02	0.6	40	0.308	190.1	199.6	27.3
7	40	0.03	0.2	50	0.251	122.9	105.8	16
8	40	0.03	0.4	40	0.273	150.5	136.3	20.1
9	40	0.03	0.6	45	0.405	241.6	244.9	34
10	55	0.01	0.2	45	0.142	51	46.1	6.8
11	55	0.01	0.4	50	0.209	132.2	99	16.2
12	55	0.01	0.6	40	0.163	120.6	132.9	17.8
13	55	0.02	0.2	50	0.239	82.9	62.5	10.2
14	55	0.02	0.4	40	0.207	116.1	114	15.9
15	55	0.02	0.6	45	0.254	149.3	180.1	23.1
16	55	0.03	0.2	40	0.229	78.7	80.4	11.1
17	55	0.03	0.4	45	0.334	139.2	135.8	19.3
18	55	0.03	0.6	50	0.416	259.7	201.2	32.4
19	70	0.01	0.2	50	0.107	44	58.7	7
20	70	0.01	0.4	40	0.108	71.2	60.5	9.2
21	70	0.01	0.6	45	0.126	104.6	114.2	15.4
22	70	0.02	0.2	40	0.164	51.7	38.4	6.3
23	70	0.02	0.4	45	0.214	94.4	121.9	15.2
24	70	0.02	0.6	50	0.326	203.8	216.2	29.5
25	70	0.03	0.2	45	0.25	60.3	73.6	9.1
26	70	0.03	0.4	50	0.39	176.2	162.2	23.5
27	70	0.03	0.6	40	0.305	131.3	115.5	17.2

3.1 The Analysis of Variance and the Mathematical Model

An ANOVA for surface roughness is shown in Table 3. Based on ANOVA, feed rate and depth-of-cut are the most influential variables regarding surface roughness. They contribute 52.76% and 21.79% to the total effect, respectively. On the other hand, the influences of input factors as cutting speed (v), feed rate (f), depth of cut (d) and hardness of workpiece (h) on surface roughness have statistical significance.

Table 3. Analysis of variance for experimental values under MQL condition

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%
ANOVA for Ra, R-Sq = 95.72%							
Model	14	0.186438	0.186438	0.013317	19.18	0.000[a]	95.72
v	1	0.004576	0.004576	0.004576	6.59	0.025[a]	2.35
f	1	0.102756	0.102756	0.102756	147.97	0.000[a]	52.76
d	1	0.042438	0.042438	0.042438	61.11	0.000[a]	21.79
h	1	0.015961	0.015961	0.015961	22.98	0.000[a]	8.19
ANOVA for Fx, R-Sq = 96.54%							
Model	14	84499.1	84499.1	6035.7	23.89	0.000[a]	96.54
v	1	7409.5	7409.5	7409.5	29.33	0.000[a]	8.47
f	1	13535.6	13535.6	13535.6	53.58	0.000[a]	15.46
d	1	49057.6	49057.6	49057.6	194.21	0.000[a]	56.05
h	1	8716.4	8716.4	8716.4	34.51	0.000[a]	9.96
ANOVA for Fy, R-Sq = 95.93%							
Model	14	85755.5	85755.5	6125.4	20.22	0.000[a]	95.93
v	1	4785.7	4785.7	4785.7	15.80	0.002[a]	5.35
f	1	10238.8	10238.8	10238.8	33.80	0.000[a]	11.45
d	1	57336.3	57336.3	57336.3	189.27	0.000[a]	64.14
h	1	7116.2	7116.2	7116.2	23.49	0.000[a]	7.96
ANOVA for Fz, R-Sq = 98.11%							
Model	14	1660.53	1660.53	118.61	44.56	0.000[a]	98.11
v	1	121.16	121.16	121.16	45.52	0.000[a]	7.16
f	1	228.98	228.98	228.98	86.03	0.000[a]	13.53
d	1	1056.47	1056.47	1056.47	396.90	0.000[a]	62.42
h	1	157.24	157.24	157.24	59.07	0.000[a]	9.29

[a]Significant

On the one hand, Table 3 also shows analysis of variance for Fx, Fy, Fz. The cutting forces get affected mostly by depth of cut followed by feed rate. Depth of cut contributes 56.05%, 64.14% and 62.42% to the total effect of the factors to Fx, Fy, Fz, respectively. Feed rate's contributions are 15.46%, 11.45% and 13.53% to the total effect of the factors to Fx, Fy, Fz, respectively. On the other hand, the influences of input factors have statistical significance on the cutting force.

A mathematical model of Ra established using RSM is shown in the following Eq. (1):

$$\mathrm{Ra} = 1.28831 - 0.00744864\,v - 15.8793f - 0.0482593\,d - 0.0404059\,h - 2.93827\mathrm{e}{-005}\,v^2 + 65.5556f^2 - 0.0194444\,d^2 + 0.000302222\,h^2 + 0.156148\,v * f - 0.00582963\,v * d + 0.000196148v * h + 7.41111f * d + 0.205778f * h + 0.0106444d * h \tag{1}$$

The coefficient of determination expresses that the mathematical model is a good model for predicting of the surface roughness under MQL condition.

Using RSM, the cutting force models are shown in the following equations:

$$\begin{aligned} Fx = {} & 1141.03 - 3.08148\,v - 5162.44f + 54.413\,d - 45.7427\,h - 0.00474074v^2 - 32333.3f^2 \\ & - 263.75\,d^2 + 0.415333\,h^2 - 30.2222\,v * f - 2.3763v * d + 0.084563\,v * h + 4465.56f * d \\ & + 201.644f * h + 10.2\,d * h \end{aligned} \tag{2}$$

$$\begin{aligned} Fy = {} & 527.606 - 7.87711\,v + 6821.74f + 157.309\,d - 18.8253\,h + 0.0276296v^2 - 160833 \\ & f^2 - 39.5833\,d^2 + 0.102\,h^2 - 45.3185\,v * f - 4.3437v * d + 0.142104\,v * h - 832.222f * d \\ & + 107.156f * h + 9.15778\,d * h \end{aligned} \tag{3}$$

$$\begin{aligned} Fz = {} & 116.209 - 0.733062\,v + 147.333f + 12.3204\,d - 4.52904\,h + 0.00145679\,v^2 \\ & - 13888.9f^2 - 20.9722\,d^2 + 0.0364444\,h^2 - 5.55556\,v * f - 0.459259\,v * d + 0.015437\,v * h \\ & + 251.111f * d + 21.5556f * h + 1.4\,d * h \end{aligned} \tag{4}$$

The coefficient of determinations expresses that the mathematical models are good models for predicting of the cutting force component under MQL condition.

3.2 Optimization of Surface Roughness and Cutting Force

Figure 1(a) shows the result of optimization for surface roughness. The optimal cutting parameters are 70 m/min for the cutting-speed, 0.01 mm/tooth for the feed-rate, 0.2 mm in the depth-of-cut, and 40 HRC for workpiece-hardness. According to these optimal cutting parameters, the minimum surface roughness of the MQL condition is 0.0868 μm, with a desirability value of 1.000. The result indicates that under MQL-cutting conditions, a higher cutting-speed, lower feed-rate, lower depth-of-cut, and lower workpiece-hardness will lead to optimal surface roughness.

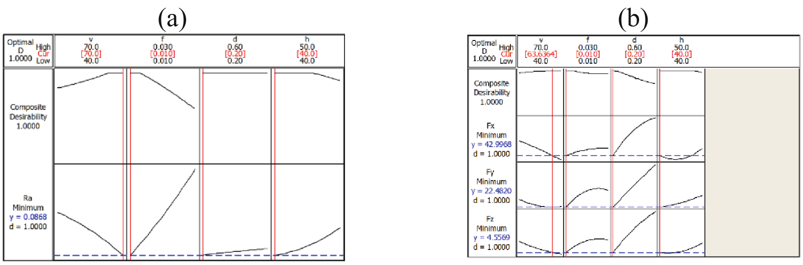

Fig. 1. The optimization plot of surface roughness (a) and cutting-force components (b)

Figure 1(b) shows the result of optimization for cutting-force components. The optimal cutting parameters are 63.636 m/min for the cutting- speed, 0.01 mm/tooth for the feed-rate, 0.2 mm in the depth-of-cut and 40 HRC for workpiece-hardness under MQL conditions. According to these optimal cutting parameters, a higher cutting-speed, lower feed-rate, lower depth-of-cut and lower workpiece-hardness will lead to minimal cutting force.

4 Conclusions

Under MQL conditions, feed rate and depth-of-cut are the most influential variables related to surface roughness. The feed rate contributes 52.76% and depth-of-cut contributes 21.79% to the total effect.

The cutting force components are principally affected by depth-of-cut, followed by the feed rate. Depth-of-cut contributes 56.05%, 64.14% and 62.42% to the total effect of the factors to Fx, Fy, and Fz, respectively. The feed rate's contributions are 15.46%, 11.45% and 13.53% to the total effect of the factors to Fx, Fy, and Fz, respectively.

A higher cutting speed, lower feed rate, lower depth-of-cut and lower workpiece hardness realized better surface roughness and minimum cutting force.

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