RESEARCH OF MULTI-RESPONSE OPTIMIZATION OF MILLING PROCESS OF HARDENED S50C STEEL USING MINIMUM QUANTITY LUBRICATION OF VIETNAMESE PEANUT OIL

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Abstract

This study aims to build a regression model when surveying the milling process on S50C steel using Minimum Quantity Lubrication (MQL) of Vietnamese peanut oil-based on Response Surface Methodology. The paper analyses and evaluates the effect of cutting parameters, flow rates, and pressures in minimum quantity lubrication system on cutting force and surface roughness in the milling process of S50C carbon steel materials after heat treatment (reaching a hardness of 52 HRC). The Taguchi method, one of the most effective experimental planning methods nowadays, is used in this study. The statistical analysis software, namely Minitab 19, is utilized to build a regression model between parameters of the cutting process, flow rates and pressures of the minimum quantity lubrication system and the cutting force, surface roughness of the part when machining on a 5-axis CNC milling machine. Thereby analyzing and predicting the effect of cutting parameters and minimum quantity lubrication conditions on the surface roughness and cutting force during machining to determine the influence level them. In this work, the regression models of R_a and F were achieved by using the optimizer tool in Minitab 19. Moreover, the multi-response optimization problem was solved. The optimum cutting parameters and lubricating conditions are as follows: Cutting velocity $V_c = 190.909$ m/min, feed rate $f_z = 0.02$ mm/tooth, axial depth of cut $a_p = 0.1$ and nozzle pressure $P = 5.596$ MPa, flow rate $Q = 108.887$ ml/h. The output parameters obtained from the above parameters are $R_a = 0.0586$ μm and $F = 162.035$ N, respectively. This result not only provides the foundation for future research but also contributes reference data for the machining process.

Keywords: milling parameters, MQL, peanut oil, surface roughness, cutting force, S50C steel, multi-response optimization.

1. Introduction

S50C steel material is high strength steel, has medium carbon content, has strong oxidation resistance, high rust and heat resistance. Another advantage of this is good polishing. For these reasons, S50C steel is widely used in the mould industry for the manufacture of injection moulds, plastic moulds. Moreover, it also used in shipbuilding, components for factory structure, and other mechanical parts, etc. There are many different methods to generate products from S50C steel materials, such as pressure forming process, casting, metal cutting. Among these methods, metal machining accounts for a relatively high proportion in the automotive manufacturing industry and machine components.

It is necessary for manufacturing enterprises to approach comprehensive researches on issues concerning economic and production efficiency in order to obtain solutions to these problems. For the reason of meeting the rocket development of the industry and the demand of highly competitive market nowadays, it is necessary to apply a reasonable plan in the machining process.

Hardened steel is generally a difficult-to-cut material, but the technology of machining this material with a tool that has cutting edges, typically hard milling, has attracted considerable attention.

In machining and manufacturing of cores and cavities of moulds, hard milling has emerged as an alternative machining method to Electrical Discharge Machining (EDM), which has a high cost and a long period of time in Machining [1, 2]. To mill hard materials, it is imperative that we have the right equipment as well as appropriate solutions, and the need for minimum quantity lubrication technology is leading to great concerns now [3, 4]. In this paper, the author emphasizes studying the simultaneous effects of cutting parameters, flow rates, and injection pressure of the minimum quantity lubrication system on surface roughness and cutting force when milling S50C steel materials after heat treatment.

The purpose of this study is to build a mathematical regression model between the input parameters: cutting speed (V_c), tooth infeed amount (f_z), cutting depth in the axial direction (a_p), pressure (P), and flow rate (Q) with surface roughness and cutting force in output when milling S50C steel after heat treatment.

The process of cutting hard materials with the indexable cutting tool experienced continuous changes in the cutting force in the whole cutting process. There are many different factors inside and outside the machining system that directly or indirectly affect the cutting force in the machining process, and some typical parameters are synthesized by the fishbone diagram in **Fig. 1** [5, 6].

Additionally, the surface roughness of the part is also one of the pivotal criteria for product evaluation. Recent studies show that the use of minimum quantity lubrication in milling has positive results in product quality and environment [7–9].
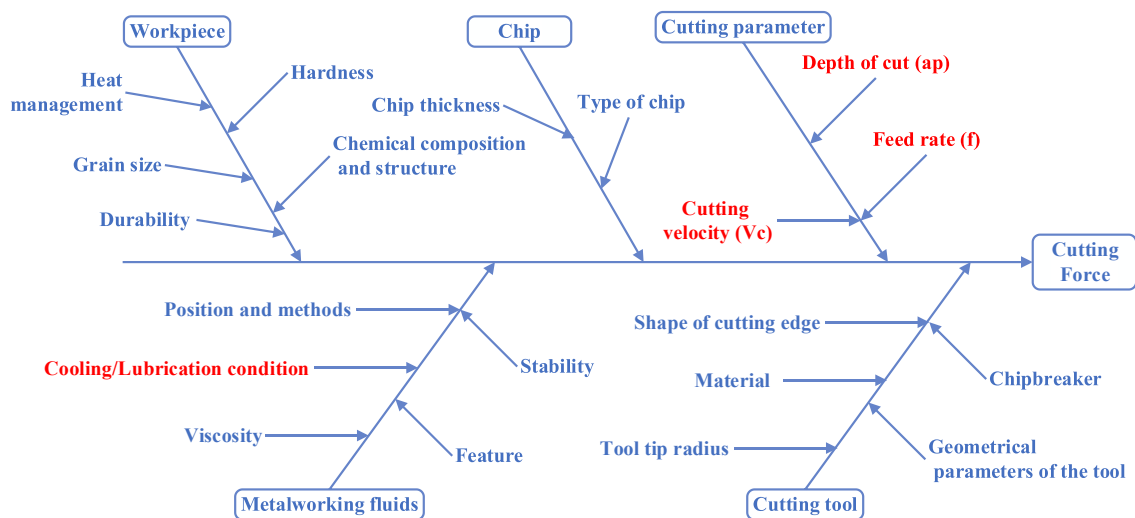

Fig. 1. Fishbone diagram of aspects affecting cutting force during machining

Over the last couple of decades, many different optimization methods were developed and presented in order to optimize surface roughness in machining, including milling, turning, and grinding. A growing market has made it necessary for manufacturers to improve product quality as well as reduce cost. Hence, multi-objective Optimization became more popular in recent years. Optimization of the milling process, especially when investigating hard materials or modern lubrication methods, is receiving a lot of attention from researchers and manufacturing companies. Optimizer approaches vary depending on the researcher's expectation of the targeted model. It has been proposed that the particle swarm optimization algorithm (PSO) be used to extract the optimal parameters in view of the boundary conditions, which can be determined through the empirical relationship of the factors that affect machining. The authors in reference [10] have used that method to show an optimization study on optimum determination of the cutting parameters and cutter helix angle when end milling of Al6061. Research on the Optimization of MQL-enabled milling processes is also attracting a great deal of interest. Mozammel Mia has been successful in Mathematical Modelling and Optimization of MQL assisted end milling characteristics based on RSM and Taguchi method [11]. In [12], the study carried out research applying RSM in multiple-response

Optimization in end milling of S50C medium carbon steel assisted MQL, concentrating on minimizing residual stress, cutting force and surface roughness.

There is a correlation between the cutting force in milling and the surface roughness of the workpiece, so it is possible to rely on the tendency of the cutting force to predict the changing pattern of the surface quality of the workpiece [13]. Thus both surface roughness and shear force must be monitored during the machining process, thereby aiming to solve the problem of online monitoring and multi-target Optimization of quality and technical indicators to help increase economic efficiency and product quality when machining [14].

2. Materials and methods

2. 1. Surveying condition

The 5 axis machining centre CNC (DMU50) with the control system of Siemens 840D (**Fig. 2**):

1) axis itinerary $X/Y/Z = 500/450/400$;

2) axis itinerary B: -5 degree to +110 degree;

3) axis itinerary C: 360 degrees;

4) main axis motor:

– main axis speed from 20 to 14.000 (round/min.);

– main axis motor capacity: 20.3 KW;

5) axis SK40 standard DIN69871;

6) working table: axis speed B and C max: 20 (round/min.);

7) toolset:

– 16 positions;

– Tool length: 300 mm;

– Tool weight: 6 kg;

8) axis moving speed:

– max machining speed in axes of $X/Y/Z$: 30.000 mm/min.;

– fast tool running speed in axes of $X/Y/Z$: 30.000 mm/min.

Fig. 2. 5-axis CNC machining centre DMG DMU50

Minimum Quantity Lubrication System (MQL): minimum lubrication system for metalworking of TOPSET, Beijing, China, is shown in **Fig. 3**. Specifications are as follows: Nozzle size: 6 mm, maximum number of nozzles: 2 nozzles. The lubricant of the minimum lubrication system in this study was peanut oil.

Cutting Tool: the experiment using EGO® Indexable End Mills with a WIDA brand cutting insert, which under the code APMT1135PDR-SPTIEH from India. Cutting diameter $(d) = 16$ mm, body diameter $(D) = 17$ mm. The number of insert positions: 2, length: 150 mm. WIDA carbide inserts coated with TiAlN, tip radius $R = 0.8$ mm. **Fig. 4** depicts the cutting tool used in this study.

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**Fig. 3.** Minimum Quantity Lubrication System

Fig. 4. Cutting tool

Cutting force measurement system: the force sensor of Swiss company Kistler is used to measure the cutting force of three components F_x, F_y, F_z. With the force measurement range from –3 KN to 3 KN, the system will receive data type 3160-B-042, then DynoWare software is used to collect and analyze the force data. The force measurement system is installed following the description in **Fig. 5**.
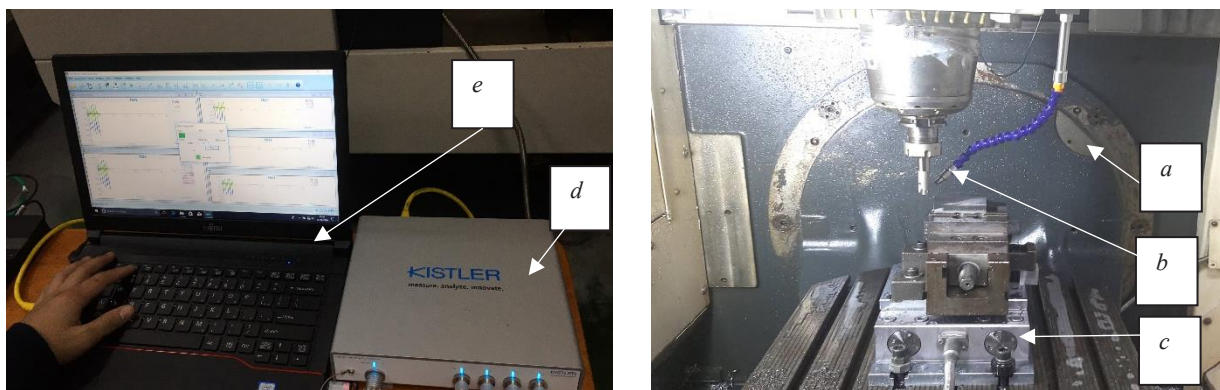
Fig. 5. Cutting force measurement system: *a* – CNC machine centre; *b* – MQL Nozzle;
c – Force sensors; *d* – Signal receiving module; *e* – Computer and software

Surface roughness measurement system: the surface roughness R_a was measured by MITUTOYO-Surftest SJ-210 Portable Surface Roughness Tester. SurfTest SJ USB Communication Tool Ver5.007 software allows displaying and storing measurement parameters R_a according to ISO 1997 standard. Each experiment was measured three times. The average value of 3 times was used to analyze and evaluate the experimental results. Details of the surface roughness measurement system are displayed in **Fig. 6**.
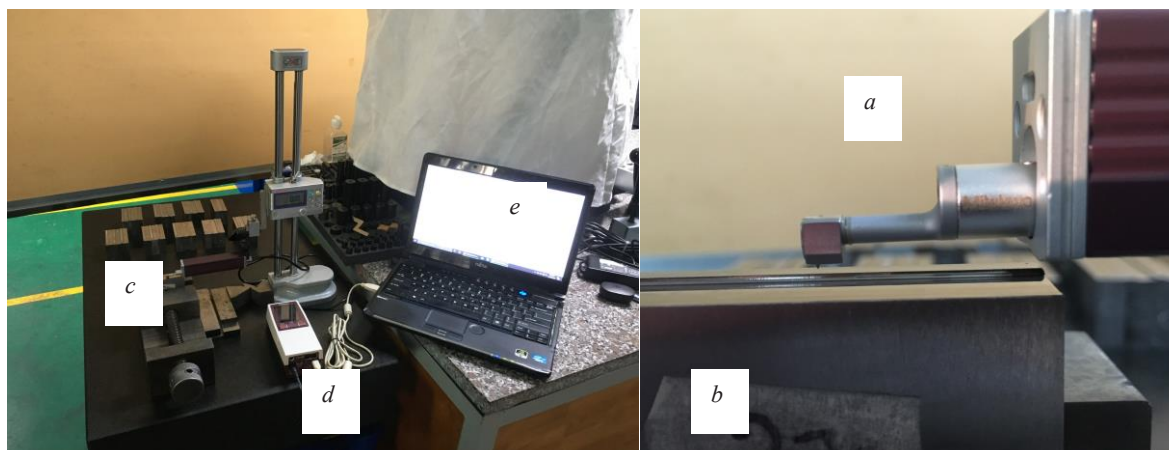
Fig. 6. The surface roughness measurement system: *a* – Measure stylus; *b* – Sample; *c* – Fixture; *d* – Data processing; *e* – Computer and software

Workpiece: experiments are carried out on JIS S50C carbon steel after heat treatment (shown in **Fig. 7**), which has 52 HRC hardness. Size of test sample $L×W×H = 70×30×15$ (mm). The chemical composition of S50C steel in **Table 1** and the specification of S50C carbon steel are shown in **Table 2**.
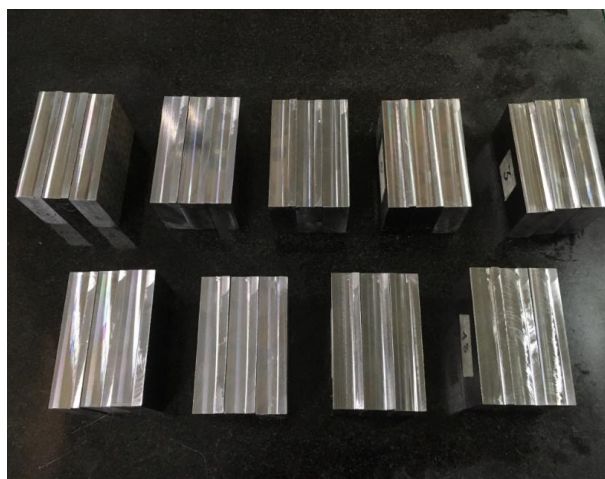
Fig. 7. Experimental sample

Table 1
The chemical composition of S50C steel

Ni+Cr≤0.35 %							
C (%)	Si (%)	Mn (%)	P (%)	S (%)	Ni (%)	Cr (%)	Cu (%)
0.47–0.53	0.15–0.35	0.6–0.9	Max 0.03	Max 0.035	Max 0.2	Max 0.2	Max 0.3

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Table 2

Technical properties of S50C steel

Properties	Value
Density (kg/m³)	8000
Poisson's Ratio	0.27–0.30
Elastic Modulus (GPa)	190–210
Tensile Strength (MPa)	1588
Yield Strength (MPa)	1034
Thermal conductivity (W/m-k)	47.2
Specific heat (J/kg-k)	477
Thermal expansion (1e-6/K)	16
Melting temperature (°C)	1370–1400
Service temperature (°C)	0–500

With the above properties and the hardness that S50C steel achieves after heat treatment, S50C steel creates difficulties in machining, especially in methods that use a cutting tool, milling for instance.

2. 2. Experimental method

Through the research model, the study conducted experiments with V_c, f_z, a_p, P and Q. Applying the empirical method Taguchi L27 orthogonal with three different levels to experimentally analyze and predict cutting force and surface roughness when milling. Based on the Taiwanese EGO® carbide cutting tool recommendation of the cutting tool manufacturer, the cutting parameters for testing S50C steel material after heat are within the following limits:

– the cutting velocity V_c on the milling machine in the range: 120÷300 m/min;

– the cutting depth in axial direction a_p: 0.1÷0.9 mm;

– the advance f_z in the range: 0.02÷0.1 mm/tooth.

Based on the facilities of the workshop and capabilities of the MQL system, the limits for the lubrication system parameters are:

– nozzle pressure P: 2÷6 MPa;

– flow rate Q: 50÷150 ml/h.

According to Taguchi orthogonal experimental planning theory, an experiment with three levels is selected and determined in **Table 3**.

Table 3

Table of experimental input parameters

TT	Parameter	Level 1	Level 2	Level 3
		−1	0	1
1	Cutting velocity (V_c), m/min	120	210	300
2	Feed rate (f_z), mm/tooth	0.02	0.06	0.1
3	Axial depth of cut (a_p), mm	0.1	0.5	0.9
4	Pressure (P), MPa	2	4	6
5	Flow rate (Q), ml/h	50	100	150

In experimental research, with five input parameters, each parameter includes 3 different levels, the most suitable experimental matrix is (L27-3⁵), including «27 selected experiments, which are shown in **Table 4**.

Table 4

Surface roughness and cutting force result

No.	Encoding					Parameters					Surface roughness R_a [μm]	Cutting force F [N]
	X_1	X_2	X_3	X_4	X_5	P	Q	V_c	f_z	a_p		
1	−1	−1	−1	−1	−1	2	50	120	0.02	0.1	0.1123	242.5857
2	−1	−1	−1	−1	0	2	50	120	0.02	0.5	0.1673	319.6112
3	−1	−1	−1	−1	1	2	50	120	0.02	0.9	0.1317	261.8555
4	−1	0	0	0	−1	2	100	210	0.06	0.1	0.1240	291.2619
5	−1	0	0	0	0	2	100	210	0.06	0.5	0.1300	600.3795
6	−1	0	0	0	1	2	100	210	0.06	0.9	0.1280	747.9208
7	−1	1	1	1	−1	2	150	300	0.1	0.1	0.1417	386.3822
8	−1	1	1	1	0	2	150	300	0.1	0.5	0.1560	694.0772
9	−1	1	1	1	1	2	150	300	0.1	0.9	0.1610	1091.7684
10	0	−1	0	1	−1	4	50	210	0.1	0.1	0.0980	234.2903
11	0	−1	0	1	0	4	50	210	0.1	0.5	0.1170	596.4672
12	0	−1	0	1	1	4	50	210	0.1	0.9	0.1650	883.1737
13	0	0	1	−1	−1	4	100	300	0.02	0.1	0.0723	296.3350
14	0	0	1	−1	0	4	100	300	0.02	0.5	0.0800	420.5361
15	0	0	1	−1	1	4	100	300	0.02	0.9	0.0930	629.3605
16	0	1	−1	0	−1	4	150	120	0.06	0.1	0.1367	259.0606
17	0	1	−1	0	0	4	150	120	0.06	0.5	0.1553	487.9602
18	0	1	−1	0	1	4	150	120	0.06	0.9	0.2423	834.1574
19	1	−1	1	0	−1	6	50	300	0.06	0.1	0.1667	234.6851
20	1	−1	1	0	0	6	50	300	0.06	0.5	0.2240	494.2717
21	1	−1	1	0	1	6	50	300	0.06	0.9	0.2400	931.3188
22	1	0	−1	1	−1	6	100	120	0.1	0.1	0.1350	239.1861
23	1	0	−1	1	0	6	100	120	0.1	0.5	0.2100	500.2546
24	1	0	−1	1	1	6	100	120	0.1	0.9	0.2770	843.2801
25	1	1	0	−1	−1	6	150	210	0.02	0.1	0.0933	162.7148
26	1	1	0	−1	0	6	150	210	0.02	0.5	0.0987	358.4126
27	1	1	0	−1	1	6	150	210	0.02	0.9	0.0900	511.9236

Since then, we are conducting experimental research on the effects of 5 parameters, including cutting speed, feed rate, axial cutting depth of machining process and pressure, the flow rate of minimum quantity lubrication system on cutting force and surface roughness in the milling process.

3. Results

3. 1. Analysis of surface roughness

The results of the analysis of variance for surface roughness when machining S50C carbon steel after heat with indexable milling cutters are listed in **Table 5**. The analysis results in these tables show that: feed rate (f_z) has the greatest influence on the surface roughness of parts after machining, with 20.56 %, the effect of cutting speed (V_c) accounts for 4.10 %, depth of axial cutting (a_p) comprise 15.14 %, the pressure of minimum quantity lubrication system (P) takes up 6.03 %. Besides, the effect of the square of the cutting force ($V_c \cdot V_c$) makes up 16.68 % and the square of the feed rate ($f_z \cdot f_z$) registries 12.14 %, while other parameters affect less than 6 % are calculated in the ANOVA analysis table (**Table 5**).

Table 5

ANOVA of surface roughness results

			Analysis of Variance				
		The following terms cannot be estimated and were removed: $P{\cdot}Q$, $P{\cdot}V_c$, $P{\cdot}f_z$, $Q{\cdot}V_c$, $Q{\cdot}f_z$, $V_c{\cdot}f_z$					
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	14	0.068560	93.12 %	0.068560	0.004897	11.59	0.000
Linear	5	0.034944	47.46 %	0.034944	0.006989	16.54	0.000
P	1	0.004439	6.03 %	0.004439	0.004439	10.51	0.007
Q	1	0.001201	1.63 %	0.001201	0.001201	2.84	0.118
V_c	1	0.003016	4.10 %	0.003016	0.003016	7.14	0.020
f_z	1	0.015138	20.56 %	0.015138	0.015138	35.84	0.000
a_p	1	0.011150	15.14 %	0.011150	0.011150	26.40	0.000
Square	5	0.026077	35.42 %	0.026077	0.005215	12.35	0.000
$P{\cdot}P$	1	0.004044	5.49 %	0.004044	0.004044	9.57	0.009
$Q{\cdot}Q$	1	0.000728	0.99 %	0.000728	0.000728	1.72	0.214
$V_c{\cdot}V_c$	1	0.012280	16.68 %	0.012280	0.012280	29.07	0.000
$f_z{\cdot}f_z$	1	0.008936	12.14 %	0.008936	0.008936	21.16	0.001
$a_p{\cdot}a_p$	1	0.000087	0.12 %	0.000087	0.000087	0.21	0.657
2-Way Interaction	4	0.007539	10.24 %	0.007539	0.001885	4.46	0.019
$P{\cdot}a_p$	1	0.002389	3.25 %	0.002389	0.002389	5.66	0.035
$Q{\cdot}a_p$	1	0.000120	0.16 %	0.000120	0.000120	0.28	0.603
$V_c{\cdot}a_p$	1	0.001968	2.67 %	0.001968	0.001968	4.66	0.052
$f_z{\cdot}a_p$	1	0.003061	4.16 %	0.003061	0.003061	7.25	0.020
Error	12	0.005069	6.88 %	0.005069	0.000422	–	–
Total	26	0.073629	100.00 %	–	–	–	–
			Model Summary				
S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC	
0.0205528	93.12 %	85.08 %	0.0301436	59.06 %	−68.65	−102.32	

The regression equation, which expresses the effect of cutting parameters and minimum lubrication condition on the surface roughness, is established. It illustrates the influence of individual parameters and the mutual interaction among inputs to surface roughness, and the summary is evaluated in ANOVA analysis **Table 5**. The comparison of the predicted results and the measured results of the surface roughness of the part after machining is described in **Fig. 8**.
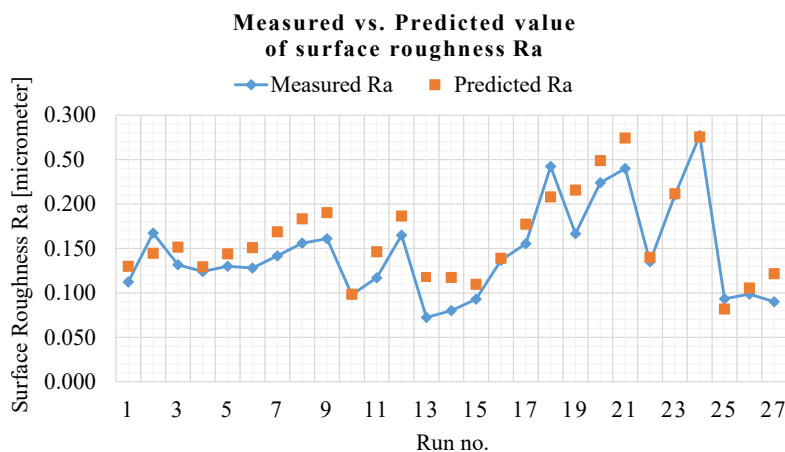
Fig. 8. Measured vs Predicted value of surface roughness R_a

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Through the description model, it shows that the predicted results are very close to the measured results. The value of R^2 of the regression equation of surface roughness reaches 93.12 %. Therefore, this mathematical regression model is the most suitable regression model with five input parameters (cutting speed, axial depth of cut, feed rate, flow rate and pressure) and the surface roughness, which is known as an output parameter:

$$\begin{cases} R_a = 0.3815 - 0.0529 \cdot P - 0.000966 \cdot Q - 0.002312 \cdot V_c + 3.120 \cdot f_z + 0.0461 \cdot a_p + \\ + 0.00649 \cdot P^2 + 0.000004 \cdot Q^2 + 0.000006 \cdot V_c^2 - 24.12 \cdot f_z^2 - 0.0238 \cdot a_p^2 + \\ + 0.01764 \cdot P \cdot a_p - 0.000158 \cdot Q \cdot a_p - 0.000356 \cdot V_c \cdot a_p + 0.998 \cdot f_z \cdot a_p, \\ R^2 = 93.12\,\%, \ R_{Ajd}^2 = 85.08\,\%. \end{cases} \qquad (1)$$

3. 2. Analysis of cutting force results

Using the ANOVA method to analyze the influence of parameters through **Table 6** shows that the axial depth (a_p) has the greatest influence on cutting force, at 62.61 %, the feed rate (f_z) registries 16,69 % and cutting speed (V_c) takes up 4.61 %, while other parameters are shown in ANOVA analysis table.

Table 6

ANOVA of cutting force results

Analysis of Variance							
The following terms cannot be estimated and were removed: $P \cdot Q$, $P \cdot V_c$, $P \cdot f_z$, $Q \cdot V_c$, $Q \cdot f_z$, $V_c \cdot f_z$							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	14	1668132	97.63 %	1668132	119152	35.26	0
Linear	5	1460160	85.46 %	1460160	292032	86.43	0
P	1	7192	0.42 %	7192	7192	2.13	0.17
Q	1	19221	1.12 %	19221	19221	5.69	0.034
V_c	1	78776	4.61 %	78776	78776	23.31	0
f_z	1	285150	16.69 %	285150	285150	84.39	0
a_p	1	1069822	62.61 %	1069822	1069822	316.61	0
Square	5	28188	1.65 %	28188	5638	1.67	0.216
$P \cdot P$	1	2546	0.15 %	2546	2546	0.75	0.402
$Q \cdot Q$	1	430	0.03 %	430	430	0.13	0.728
$V_c \cdot V_c$	1	2869	0.17 %	2869	2869	0.85	0.375
$f_z \cdot f_z$	1	21994	1.29 %	21994	21994	6.51	0.025
$a_p \cdot a_p$	1	349	0.02 %	349	349	0.1	0.753
2-Way Interaction	4	179783	10.52 %	179783	44946	13.3	0
$P \cdot a_p$	1	18301	1.07 %	18301	18301	5.42	0.038
$Q \cdot a_p$	1	5848	0.34 %	5848	5848	1.73	0.213
$V_c \cdot a_p$	1	23994	1.40 %	23994	23994	7.1	0.021
$f_z \cdot a_p$	1	131641	7.70 %	131641	131641	38.96	0
Error	12	40547	2.37 %	40547	3379	–	–
Total	26	1708679	100.00 %	–	–	–	–
Model Summary							
S	*R*-sq	*R*-sq(adj)	PRESS	*R*-sq(pred)	AICc	BIC	
58.1287	97.63 %	94.86 %	250310	85.35 %	360.51	326.84	

The regression equation, which expresses the effect of cutting parameters and minimum lubrication condition on the surface roughness, is constructed. It depicts the influence of individual

parameters and the mutual interaction among inputs to cutting force, and the summary is evaluated in ANOVA analysis **Table 6**. The comparison of the predicted results and the measured results of the cutting force is described in **Fig. 9**.
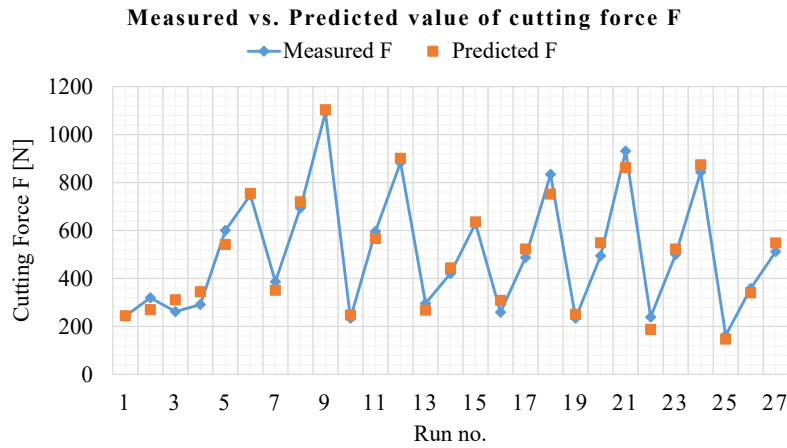
Fig. 9. Measured vs Predicted value of cutting force F

Through the description model, it shows that the predicted results are very close to the measured results. The value of R^2 of the regression equation of surface roughness reaches 97.63 %. Thus, this mathematical regression model is the most suitable regression model with five input parameters (cutting speed, axial depth of cut, feed rate, flow rate and pressure) and the cutting force, which regarded as another output parameter of the model:

$$
\begin{cases}
F = 227 + 6.8 \cdot P + 0.78 \cdot Q - 1.02 \cdot V_c + 4414 \cdot f_z - 397 \cdot a_p - 5.15 \cdot P^2 - \\
- 0.00338 \cdot Q^2 + 0.00270 \cdot V_c^2 - 37841 \cdot f_z^2 + 48 \cdot a_p^2 + 48.8 \cdot P \cdot a_p + \\
+ 1.104 \cdot Q \cdot a_p + 1.242 \cdot V_c \cdot a_p + 6546 \cdot f_z \cdot a_p, \\
R^2 = 97.63\,\%,\ R_{Ajd}^2 = 94.86\,\%.
\end{cases}
\tag{2}
$$

3. 3. Multi-respond Optimization of surface roughness and cutting force
3. 3. 1. Surface roughness (R_a)

Taguchi analysis method of Minitab software is used to find out the influence of pressure (P), flow rate (Q), cutting speed (V_c), feed rate (f_z) and axial cutting depth (a_p) to surface roughness (R_a) (**Table 7**). As a result, we have a chart in **Fig. 10** to evaluate the influence of cutting parameters and the lubrication conditions on surface roughness. The graph shows that the surface roughness tended to decrease slightly from 0.14 μm to less than 0.13 μm while puts the pressure (P) from level 1 to level 2. And a significant growth is seen in the surface roughness when P moves up to level 3, increasing to more than 0.17 μm. When the flow rate (Q) underwent an increase from level 1 (50 ml/h) to level 2 (100 ml/h), the surface roughness decreases considerably from 0.16 μm to 0.14 μm. However, after that, this value tends to climb slightly to more than 0.14 μm at level 3 of the flow rate.

Table 7

Response Table for Means of R_a

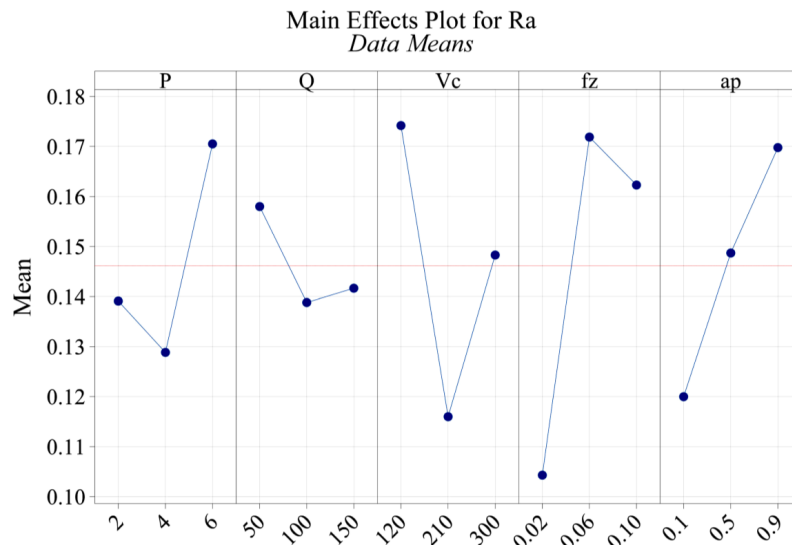| Level	P	Q	V_c	f_z	a_p
1	0.1391	0.1580	0.1742	0.1043	0.1200
2	0.1289	0.1388	0.1160	0.1719	0.1487
3	0.1705	0.1417	0.1483	0.1623	0.1698
Delta	0.0417	0.0192	0.0582	0.0676	0.0498
Rank	4	5	2	1	3

Fig. 10. Main Effects Plot for Means of R_a

Cutting velocity (V_c) parameters have a similar pattern to pressure (P) and flow rate (Q), but V_c shows a more pronounced effect. Cutting velocity grew from level 1 (120 m/min) to level 2 (200 m/min) made the surface roughness has had a significant improvement. The surface roughness value decreased noticeably from nearly 0.18 μm to approximately 0.11 μm. Surface roughness is influenced most by feed rate (f_z). Specifically, the graph shows that the surface roughness increased sharply when set the feed rate from level 1 to level 2, climbing from 0.07 μm to 0.18 μm. It hits the peak at that value and decreases slightly to 0.16 μm when adjusting the feed rate to level 3. Ranked third among the most influential parameter for surface roughness is the axial depth of cut (a_r). The statistics illustrate that if the depth of cut increases gradually from level 1 (0.1mm) to level 2 (0.5 mm) and level 3 (0.9 mm), the surface roughness witnessed a rapid increase to 0.15 μm and 0.17 μm, respectively.

3. 3. 2. Cutting force (F)

Similarly, we analyze to find out the influence of pressure (P), flow rate (Q), cutting velocity (V_c), feed rate (f_z) and cutting depth in the axial direction (a_p) on the cutting force during the milling process (**Table 8**). Thus, we got a chart that evaluates the influence of cutting parameters and minimum lubricating parameters on the cutting force when machining (**Fig. 11**). The biggest influence on the cutting force in the surveyed parameters belongs to axial cutting depth (a_p). The cutting force increases rapidly from 280 N at level 1 (0.1 mm) up to approximately 800 N at level 3 (0.9 mm). Followed close to that, the feed rate (f_z) and the cutting velocity (V_c) ranked 2nd and 3rd, respectively. Both these two factors boost up the cutting force F. Noticeable growth in shear force (F), about 300 N, is reported in **Fig. 11**. That increase makes the cutting force (F) reaches more than 600 N at the third level (0.1 mm/tooth) of the feed rate (f_z), from just over 300 N at level 1 (0.02 mm/tooth).

Table 8

Response Table for Means of F

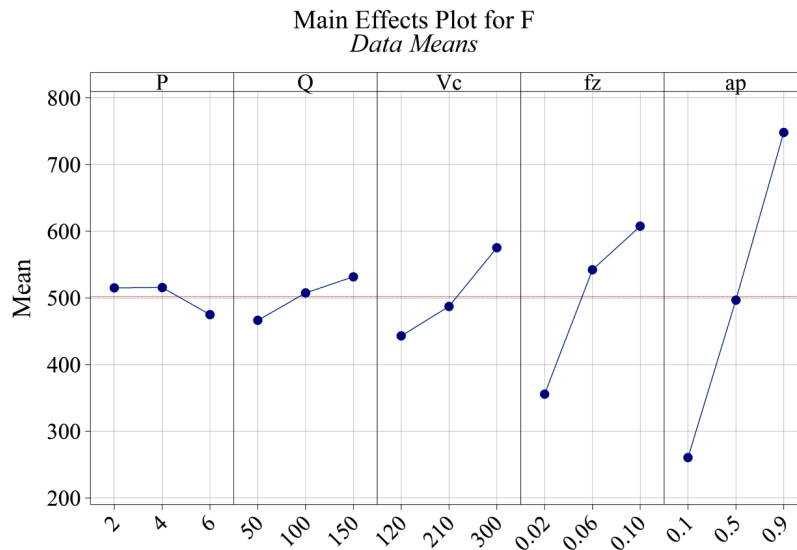| Level	P	Q	V_c	f_z	a_p
1	515.1	466.5	443.1	355.9	260.7
2	515.7	507.6	487.4	542.3	496.9
3	475.1	531.8	575.4	607.7	748.3
Delta	40.6	65.4	132.3	251.7	487.6
Rank	5	4	3	2	1

Fig. 11. Main Effects Plot for Means of F

It should be noted that cutting speed (V_c) has the same tendency to affect cutting force (F) with feed rate (f_z), starting with a value of about 450 N at the first level, the cutting force F has increased to 500 N at the second level (210 m/min) and continues to increase when adjusting the cutting speed (V_c) to the 3rd level (300 m/min) reaches nearly 600 N.

While the influence of the cutting parameters on the cutting force during machining shows a strong and pronounced impact, the effects of two parameters of the MQL system, including nozzle pressure (P) and oil flow rate (Q), on cutting force (F) is insignificant. Cutting force (F) changes through the investigated levels of pressure (P) and flow rate (Q) is not much. Over three levels of flow rate (Q), the cutting force (F) increases moderately, and the opposite is true when observing the cutting force at various pressure (P) levels. However, a fluctuation around 500 N was experienced in the value of F in those cases.

3. 3. 3. Multiple response optimization

In this study, Minitab 19 is employed here to solve multiple-object optimization problems by using the response surface optimization tool. The results of the analysis are shown in **Tables 9–12** and **Fig. 12**. Statistical data from **Tables 9–12** show that the surface roughness and cutting force are minimized at the value of $R_a = 0.0586$ μm and $F = 162.035$ N. To achieve mentioned optimum results, the values of the parameters in the milling process are the cutting speed $V_c = 190.909$ m/min, feed rate $f_z = 0.1$ mm/tooth, depth of cut in the axial direction $a_p = 0.1$ mm. Along with that are the parameters of the lubrication system, including nozzle pressure (P) and flow rate (Q), which are 5.595 MPa and 108.887 ml/h, respectively.

Table 9

Parameters of Multiple Optimization Problems

Response	Goal	Lower	Target	Upper	Weight	Importance
F	Minimum	–	162.715	1091.77	1	1
R_a	Minimum	–	0.072	0.28	1	1

Table 10

The Solution of Multiple Optimization Problems

Solution	P	Q	V_c	f_z	a_p	F Fit	R_a Fit	Composite desirability
1	5.59596	108.887	190.909	0.02	0.1	162.035	0.0586210	1

Table 11

The prediction setting value of Multiple Optimization

Variable	Setting
P	5.59596
Q	108.887
V_c	190.909
f_z	0.02
a_p	0.1

Table 12

The Multiple Response Prediction of Multiple Optimization

Response	Fit	SE Fit	95 % CI	95 % PI
F	162.0	41.1	(72.5, 251.5)	(7.0, 317.1)
R_a	0.0586	0.0145	(0.0270, 0.0903)	(0.0038, 0.1135)
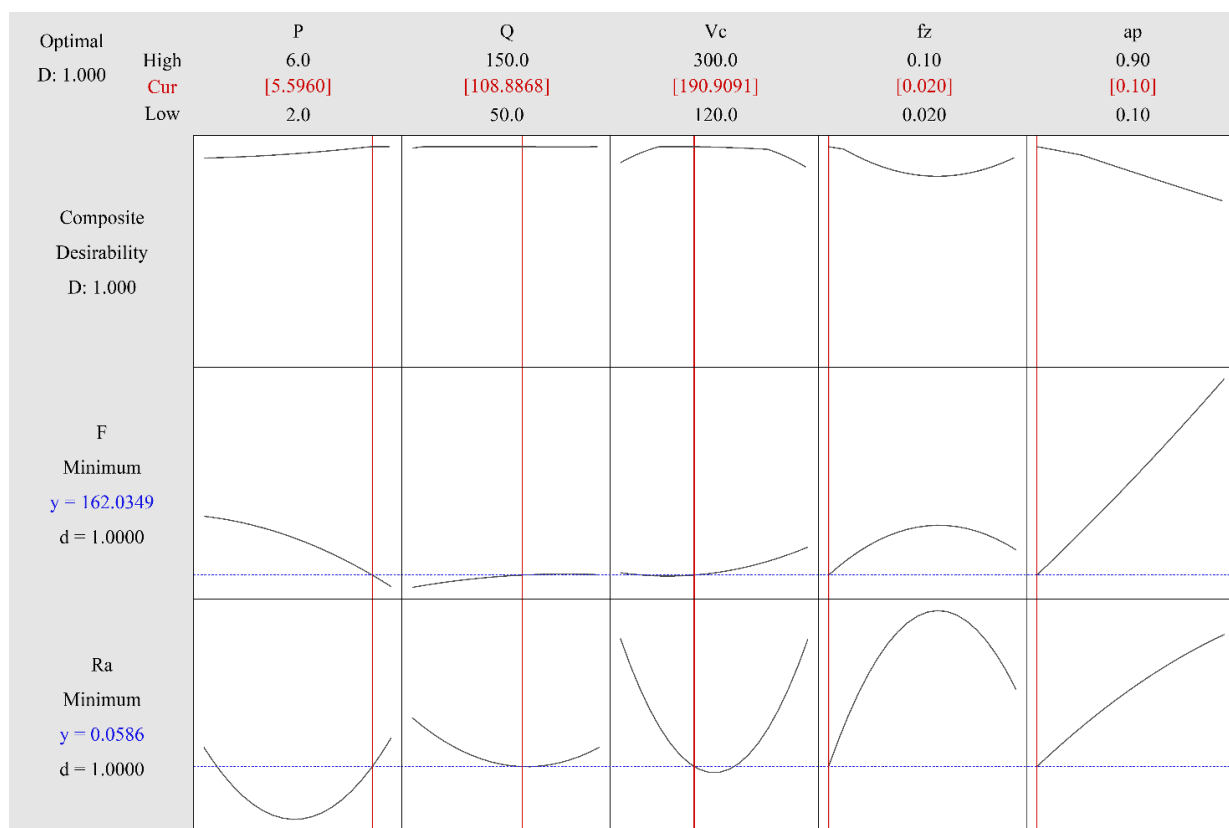
Fig. 12. Multiple Optimization of R_a and F

4. Discussion

The analysis results for surface roughness showed that the influence of cutting parameters, including V_c, f_z and a_p, on surface roughness is substantial, while the settings for the minimum lubrication system make a trivial impact (**Table 7**, **Fig. 10**). During machining, surface roughness is characterized by scratches that cutting tools leave on the surface of the part after machining. Obviously, the minimum quantity lubrication system is not directly involved in that process, so it affects restrictedly the surface roughness.

The analysis results for the cutting force illustrated that this output parameter was influenced considerably by the cutting parameters, especially the axial depth of the cut – a_p (**Fig. 11**).

In contrast, the influence of the minimum quantity lubrication system parameters was insignificant (**Table 8**). The cutting force during machining is known as the measured value from the interaction between the cutting tool and the workpiece under a certain situation (cutting condition). In this case, the minimum lubrication system acted as a supporter in the machining to make it worked more efficiently. Thus their effect may not be apparent.

Based on the multiple response optimization results, with the criteria of minimizing both surface roughness and cutting force, it is statistically reported that the factors that were considered to have the greatest influence on surface roughness and cutting force, which were f_z and a_p in respective order, were predicted to set in the lowest level (**Fig. 12**). This demonstrates the consistency of the study.

In this study, the effects of parameters of the minimum lubrication system on surface roughness and cutting force are not clear (**Fig. 10, 11**). This research stops at the evaluation of the milling process of S50C steel after heat treatment with the aid of MQL. And it also wants to find out how the MQL system impacts the machining process, while it already has various recognized advantages such as minimizing cooling fluids waste and impact positively on the environment. Therefore, the study focuses on evaluating the influence of input parameters on output parameters and predicting multi-object optimization settings for output parameters.

It is also important to notice that the investigation range of the MQL system parameters is limited by the workshop facilities and experimental equipment. Therefore, it is possible that the study may not touch the values that cause a huge change in results yet. This study is limited to an experimental study investigating five input parameters, including three cutting parameters (V_c, f_z, a_p) and two parameters of the MQL system (P and Q). Other important machining parameters such as system vibration, tool wear, material removal rate, etc. have not been included to evaluate cutting force and surface roughness in this study. In the future, comprehensive studies on input and output parameters, in order to optimize productivity, tool life, etc in the hard milling process, will be the directions for further development of this research.

5. Conclusions

The paper has conducted experiments to survey and analyze the effects of cutting parameters as well as parameters of minimum lubrication conditions (V_c, f_z, a_p and Q, P) when milling S50C hardened steel after heat treatment. The research applied Taguchi experimental planning method to design and evaluate experiments. Besides, the software called Minitab 19 was used as a tool to build experimental regression mathematical models between input parameters (consist of cutting parameters and MQL conditions) and output parameters, which are the product's surface roughness and cutting force during machining, depicting in equations (1) and (2) in respective order.

The results show that the surface roughness is majorly affected by feed rate f_z (20.56 %), cutting speed V_c (4.10 %), depth of cut axial direction (15.14 %), minimum quantity lubrication system pressure P (6.03 %), injection oil flow rate Q (1.63 %) and square of cutting speed $V_c \cdot V_c$ (16.68 %), squared of feed rate $f_z \cdot f_z$ (12.14 %).

Cutting force during machining (F) mainly corresponds to the influence levels of the depth of cut in the axial direction (62.61 %), feed rate f_z (16.69 %), cutting velocity V_c (4.61 %), oil flow rate Q (1.12 %), nozzle pressure P (0.42 %) and interaction between feed rate and axial cutting depth a_p (7.70 %).

The combining milling parameters and lubricant condition as following: the cutting velocity V_c of 190.909 m/min, feed rate f_z of 0.1 mm/tooth, axial depth of cut of 0.1 mm and oil flow rate, air pressure of 108.887 ml/h, 5.595 MPa, respectively. Corresponding to the surface roughness R_a and cutting force F of 0.0586 μm, 163.035 N.

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