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Effect of Cutting Parameters on Cutting Force and Surface Roughness of Workpiece When Milling 40Cr Steel Using PVD-Coated Cutter

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Abstract-In this paper, experimental research has been carried out to determine the effects of cutting parameters on cutting force and surface roughness when milling steel 40Cr. The cutting parameters mentioned in this study include the cutting speed, the feed rate and the depth of cut. The cutting tool used in this study is a face mill tool with the cutting edges coated with PVD. The results have determined the level and rule of effect of cutting parameters as well as the effect of the interactions of these parameters on cutting force and surface roughness. The relationship between cutting force, surface roughness and cutting parameters was also established in this study. The reliability of these relationships has been verified by analyzing the graph comparing the probability of distributing the residuals against the normal distribution (Probability plot) and the graph representing the relationship between the residuals and corresponding values of regression model (Versus order plot).

Keywords- *Cutting Parameters, Cutting Force, Surface Roughness, Face Milling, 40Cr Steel, PVD Coated Milling Cutter*

I. INTRODUCTION

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Milling is a popular processing method, with high productivity and is widely applied in mechanical processing. Milling methods can be used to process a variety of surfaces, with a variety of materials. Surface roughness has a great effect on the shelf life of products and is often chosen as one of the criteria to evaluate the efficiency of milling processes [1- 4]. Besides surface roughness parameter, cutting force is often chosen as an indicator to evaluate the efficiency of the milling process, because cutting force is a parameter that reflects the energy consumption (through cutting power). [5-9]. Researching on the milling process to find solutions to reduce cutting force and reduce surface roughness when milling has been conducted by many authors. Among them, the authors often focus on the study of the effect of cutting parameters on surface roughness and cutting force when milling, the results of those studies are the basis for the selection of parameters of cutting parameters in each specific condition.

Tien Dung Hoang et al. [10] when studying the milling of SKD61 steel concluded: The amplitude of cutting force will increase if the value of depth of cut and the feed rate increase. Jhy-Cherng Tsai et al. [11] studied the milling of the material Inconel 718 using a face mill tool with the cutting edges made of TiAlN-coated material. Their research concluded: All three parameters of the cutting parameters had a significant effect on the cutting force. In particular, if the depth of cut increases, the cutting force will increase. Wen-Hsiang Lai [5], in the study of cutting force model, has come to the conclusion: depth of cut has the greatest effect on cutting force, as increasing depth of cut will result in rapid increase of cutting force. The study of Md. Anayet U Patwar et al. [12] concluded: (1) The feed rate has the greatest effect on the cutting force, followed by the effect of depth of cut, cutting speed doesn’t have much effect to tangent force component; (2) Increasing the feed rate and the depth of cut increases the cutting force. As for the cutting speed, increasing the value of this parameter sometimes increases, sometimes reduces the cutting force. Erol Kilickap et al. [8] studied Ti-6242S alloy milling and made the following conclusions: (1) The feed rate, cutting speed and depth of cut have a significant effect on cutting force; (2) The cutting force increases if the value of the depth of cut is increased and the value of the cutting speed is decreased. When increasing the value of the feed rate, the value of the cutting force increases rapidly. Hasan Gökkaya [13], when experimenting with AA2014 (T4) alloy milling, showed the results: (1) The feed rate has a significant effect on the cutting force. Increasing the feed rate increases the value of the cutting force; (2) Cutting speed has negligible effect on cutting force. When the cutting speed changes 2.5 times (from 200 m/min to 500 m/min), the cutting force changes very little. Pathak et al. [14] studied the process of milling two types of alloys, Al-1Fe-1V-1Si and Al-2Fe-1V-1Si, commented: (1) Cutting parameters have significant effect on cutting force when processing both materials; (2) When increasing the value of depth of cut and the feed rate, the cutting force increases, while increasing the value of cutting speed, the cutting force decreases.

Pham Thi Hoa et al. [15] when milling A6061 aluminum alloy with a face mill tool with the cutting edges made of hard alloy (symbol APMT1604PDTR TC300) made the following remarks: (1) When the cutting speed is changed in the range speed from 356 m/min to 659 m/min and cutting conditions remain the same, the surface roughness decreases; (2) The feed rate and depth of cut increase, the surface roughness increases. Erol Kilickap et al. [8] when studying Ti-6242S alloy milling concluded that: (1) All three cutting parameters have a significant effect on surface roughness; (2) If you increase the value of the feed rate and the depth of cut, the surface roughness increases. Conversely, surface roughness decreases if the value of the cutting speed is increased. Okokpujie Imhade et al. [9] tested milling 6061 aluminum alloy under the condition of Minimum Quantity Lubrication (MQL) by a hight speed steel tool and made the following comment: (1) The interaction between cutting speed and feed rate has a great effect on the surface roughness; (2) The cutting speed affects surface roughness more than the feed rate. The study of Mohammed T. Hayajneh et al. [2] concluded: (1) The feed rate has the greatest effect on surface roughness, followed by the effect of cutting speed, depth of cut has the smaller effect surface roughness than that of feed rate and cutting speed; (2) The interaction between the feed rate and depth of cut has the strongest effect on surface roughness, followed by the effect of the interaction between cutting speed and feed rate, the interaction between cutting speed and depth of cut do not significantly affect surface roughness. Huu-That Nguyen et al. [16] studied the effect of cutting mode and the hardness of machining material (H) on surface roughness when milling SKD61 steel, they made the following remarks: All three cutting parameters including cutting speed, feed rate, cutting depth and the hardness machining material have a significant effect on surface roughness. The effect of cutting speed and the feed rate on surface roughness when milling AISI 316L SS has been empirically studied by Muhammmad Yasir et al. [17], the cutting tools they used in this study was a face mill with the cutting edges coated by WC layer. From the experimental results, they concluded: (1) Both the feed rate and the cutting speed have a significant effect on surface roughness. In particular, the effect of feed rate to surface roughness is greater than that of the cutting speed; (2) The effect of feed rate and cutting depth on surface roughness is quite complicated, when increasing the value of these two parameters, sometimes increases, sometimes decreases the value of surface roughness. Dražen Bajić et al. [3] conducted an experiment of 42CrMo4 steel milling with TiN-coated cutting tools, then they made the following remarks: (1) the cutting speed has a very little effect on surface roughness. (2) For the feed rate, when machining with a fixed cutting depth, the effect of the feed rate on surface roughness is greater than when machining with a variable cutting depth. Tien Dung Hoang et al. [10], when studying SKD61 steel milling, concluded that the feed rate is the parameter that has the most effect on surface roughness. When reducing the feed rate, increase the cutting speed from 0 to 130 mm/min, increase the depth of cut from 0 to 0.3mm, the surface roughness decreases. Nguyen Thanh Binh et al. [18] studied SKD11 steel milling, they made the comment: when increasing the feed rate and depth of cut, the surface roughness increases, but the effect of depth of cut on surface roughness is smaller than the effect of feed rate and cutting speed. Pathak et al. [14] studied the milling of two alloys, Al-1Fe-1V-1Si and Al-2Fe-1V-1Si, from which they made the comment: (1) all three parameters of the cutting parameters has almost negligible effect on surface roughness when milling alloy 1Fe-1V-1Si; (2) When milling Al-2Fe-1V-1Si alloys, the cutting parameters have a significant effect on Rz value. But for Ra value, the cutting parameters have a negligible effect. Hasan Gökkaya [13] when experimenting with AA2014 (T4) alloy milling has received results: (1) feed rate has a significant effect on surface roughness, while cutting speed has a negligible effect on surface roughness; (2) Increasing the value of feed rate will increases the value of surface roughness, while the effect of cutting speed to surface roughness is quite complicated, when increasing the value of cutting speed, the value of surface roughness sometimes increases, sometimes reduces. The experimental milling process of AISI 304 steel was done by Luis Wilfredo Hernández-González et al. [19], they came to the following conclusion: both the cutting speed and feed rate have a great effect on surface roughness. Between them, the cutting speed has a greater effect on the surface roughness more than the feed rate.

The comprehensive studies mentioned above have shown that, although there have been many studies on the effect of cutting parameters on cutting force and surface roughness when milling are published, in each specific processing condition, the level and rule of effect of cutting parameters on cutting force and surface roughness are different. Thus, in order to apply research results into production, it is necessary to conduct experimental research with each specific processing conditions of machining materials and cutting tools. In this paper, a research will be conducted to determine the effect of cutting parameters on cutting force and surface roughness when milling 40Cr steel using a PVD-coated cutter.

II. MILLING EXPERIMENT

A. Workpiece Material

The experimental material is 40Cr steel, with the chemical composition shown in Table I. This is a steel commonly used in mechanical engineering, with good machining prices, often used to make parts of static load, sometimes also for manufacturing impact-resistant components in the process of work, the parts with abrasion-resistant surfaces, such as shaft types, gears.

TABLE I. CHEMICAL COMPOSITES OF 40CR STEEL

Components	C	Si	Mn	P	S	Cr
%	0.4	0.4	0.75	0.025	0.02	1.05

B. *Milling Machine And Tool*

In Figure 1 is an experiment machine with the symbol DOOSAN DNM 400 (Korea). The cutting tool used in this study is a face cutter with 4 cutting pieces coated with PVD (Figure 2).

Figure 1. Milling machine

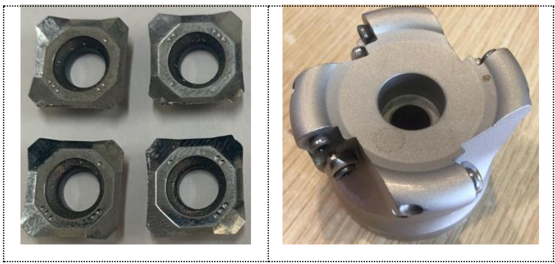


Figure 2. Milling tool

C. *Experimental Design*

Central composite design matrix is used to design experiments in this study with three cutting parameters including the cutting speed, feed rate and depth of cut. Central composite design is a design formed by a combination of 2k design (k is the number of input parameters), 2*k axial test points and a number of experimental points at the center [20]. The values of the cutting parameters at the coding levels are shown in Table II. Experimental matrix is shown in Table III.

TABLE II. INPUT PARAMETERS

Cutting parameter	Symbol	Value at leves				
		-1.68	-1	0	1	-1.68
Cuiting speed (m/min)	v	120	146.35	185	223.65	250
Feed rate (mm/tooth)	f	0.08	0.1	0.13	0.16	0.18
Depth of cut (mm)	t	0.2	0.281	0.4	0.519	0.6

TABLE III. EXPERIMENT MATRIX AND RESULTS

No.	Code	Real	I (A)	Ncut (KW)	Pc (N)	Ra (µm)	No.	Code	Real	I (A)	Ncut (KW)
	v	f	t	v, m/min	f, mm/ tooth	t mm	Bef.	In			
1	-1	-1	-1	146.35	0.10	0.281	95	119	9.12	62.32	0.26
2	1	-1	-1	223.65	0.10	0.281	96	103	2.66	11.89	0.47
3	-1	1	-1	146.35	0.16	0.281	105	112	2.66	18.18	0.78
4	1	1	-1	223.65	0.16	0.281	92	111	7.22	32.28	0.86
5	-1	-1	1	146.35	0.10	0.519	92	138	17.48	119.44	0.65
6	1	-1	1	223.65	0.10	0.519	92	110	6.84	30.58	0.40
7	-1	1	1	146.35	0.16	0.519	92	100	3.04	20.77	0.27
8	1	1	1	223.65	0.16	0.519	90	102	4.56	20.39	0.15
9	-1.68	0	0	120	0.13	0.4	91	99	3.04	25.33	0.16
10	1.68	0	0	250	0.13	0.4	91	110	7.22	28.88	0.26
11	0	-1.68	0	185	0.08	0.4	91	103	4.56	24.65	0.18
12	0	1.68	0	185	0.18	0.4	90	108	6.84	36.97	1.48
13	0	0	-1.68	185	0.13	0.2	90	110	7.6	41.08	0.99
14	0	0	1.68	185	0.13	0.6	89	101	4.56	24.65	0.13
15	0	0	0	185	0.13	0.4	91	100	3.42	18.49	0.29
16	0	0	0	185	0.13	0.4	90	102	4.56	24.65	0.26
17	0	0	0	185	0.13	0.4	90	102	4.56	24.65	0.37
18	0	0	0	185	0.13	0.4	90	105	5.7	30.81	0.34
19	0	0	0	185	0.13	0.4	90	109	7.22	39.03	0.57
20	0	0	0	185	0.13	0.4	90	112	8.36	45.19	0.41

D. *Instrumentation*

Surface roughness was measured by surface roughness tester SJ201 (Mitutoyo - Japan). For each component, measurements were made at least three times. The roughness value at each test is the average of successive measurements.

Using an electric current meter to measure the current before and during the cut at each test. From that, determining the cutting power (Ncut) and cutting force (Pc) by the following two formulas:

$$N_{cut} = U*I \quad (1)$$

$$P_C = N_{cut}/v \quad (2)$$

Cutting force values and surface roughness are summarized in the table III.

III. RESULT ANALYSIS AND DISCUSSION

Conducting analysis of experimental results in table III. ANOVA analysis results for P_C and Ra are presented in tables IV and V, respectively.

From the results in Table IV shows:

The cutting speed has the greatest influence on the cutting force, followed by the influence of feed rate, the depth of cut has the least influence on the cutting force.

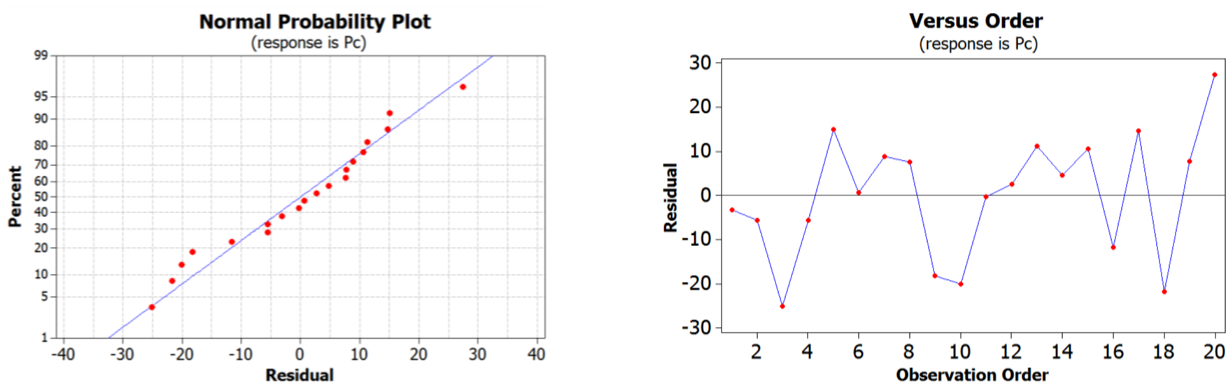
As the cutting speed and feed rate increases, the cutting force decreases. Meanwhile, the value of cutting force will increase if the value of depth of cut increases.

TABLE IV. ANOVA ANANYSIS FOR PC

ANOVA								
	df	SS	MS	F	Sig. F			
Reg.	9	6420.68	713.41	1.925	0.1610			
Res.	10	3706.65	370.67					
Total	19	10127.3						
	Coef.	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Inte.	30.1615	7.8516	3.8414	0.0033	12.6671	47.6560	12.6671	47.6560
v	-8.7657	5.2120	-1.682	0.1235	-20.3788	2.8475	-20.379	2.8475
f	-8.2018	5.2120	-1.574	0.1466	-19.8150	3.4113	-19.815	3.4113
t	2.8515	5.2120	0.5471	0.5963	-8.7617	14.4646	-8.7617	14.4646
v*v	0.7632	5.0796	0.1502	0.8836	-10.5549	12.0813	-10.555	12.0813
f*f	2.0759	5.0796	0.4087	0.6914	-9.2422	13.3940	-9.2422	13.3940
t*t	2.8040	5.0796	0.5520	0.5931	-8.5141	14.1221	-8.5141	14.1221
v*f	19.1263	6.8068	2.8099	0.0185	3.9597	34.2928	3.9597	34.2928
v*t	-6.6138	6.8068	-0.972	0.3541	-21.7803	8.5528	-21.780	8.5528
f*t	-10.6388	6.8068	-1.563	0.1491	-25.8053	4.5278	-25.805	4.5278

TABLE V. ANOVA ANANYSIS FOR RA

ANOVA								
	df	SS	MS	F	Sig. F			
Reg.	9	1.6462	0.1829	3.2379	0.0406			
Res.	10	0.5649	0.0565					
Total	19	2.2111						
	Coef.	Standard Error	t Stat	P-value	Lower95%	Upper 95%	Lower 95.0%	Upper 95.0%
Inte.	0.3753	0.0969	3.8715	0.0031	0.1593	0.5912	0.1593	0.5912
v	0.0055	0.0643	0.0858	0.9333	-0.1378	0.1489	-0.1378	0.1489
f	0.1802	0.0643	2.8013	0.0188	0.0369	0.3236	0.0369	0.3236
t	-0.1725	0.0643	-2.6810	0.0231	-0.3159	-0.0291	-0.3159	-0.0291
v*v	-0.0711	0.0627	-1.1346	0.2830	-0.2109	0.0686	-0.2109	0.0686
f*f	0.1475	0.0627	2.3523	0.0405	0.0078	0.2872	0.0078	0.2872
t*t	0.0524	0.0627	0.8352	0.4231	-0.0873	0.1921	-0.0873	0.1921
v*f	-0.0012	0.0840	-0.0138	0.9893	-0.1884	0.1861	-0.1884	0.1861
v*t	-0.0820	0.0840	-0.9762	0.3520	-0.2693	0.1052	-0.2693	0.1052
f*t	-0.1915	0.0840	-2.2786	0.0459	-0.3787	-0.0042	-0.3787	-0.0042



(a) (b)

Figure 3. Normal Probability and Versus order plot for Pc. a) Normal Probability plot, b) Versus order plot

The interaction between the cutting speed and the feed rate has an effect on the cutting force greater than the influence of the interaction between the feed rate and the depth of cut. The interaction between cutting velocity and depth of cut has the least influence on cutting force.

Also from Table IV, the relationship between cutting force and cutting parameters is shown as in equation (3). This equation is the basis for determining the value of the cutting parameters to ensure that the machining force will reach the minimum value. Regarding the reliability of this relationship, we can observe the graph the Normal Probability (displayed in points) compared with the standard distribution (displayed by the straight line) and Versus order plot - the graph shows the relationship between the balances and the corresponding value of versus order as shown in Figure 3.

$$P_C = 30.162-8.766*v-8.202*f+2.8515*t+0.763*v^2+2.076*f^2 +2.804*t^2+19.1263*v*f-6.614*v*t-10.639*f*t \quad (3)$$

Observing Figure 3a shows that the distributions are very close to the normal distribution, while Figure 3b shows the random distribution points, without any rules, proving that the data on cutting force in Table III is not affected by any other control element than the cutting parameters. This confirms the relationship between cutting force and cutting parameters very reliably.

Observing Table V shows:

The feed rate has the greatest impact on surface roughness, followed by the extent to which the depth of cut is affected, and the cutting speed has a negligible effect on surface roughness. Increasing the feed rate will increase the surface roughness. Meanwhile, the surface roughness will decrease if the depth of cut increases.

Only the interaction between the feed rate and the depth of cut has a significant effect on surface roughness. The interaction between the cutting speed and the feed rate, the interaction between the cutting speed and the depth of cut have a negligible effect on surface roughness.

For surface roughness, the graph compares the Normal Probability compared to the normal distribution and the graph shows the relationship between the balances and the corresponding value of the Versus order is shown in Figure 4.

The observation of Figure 4a also shows that the distribution is very close to the normal distribution, while in Figure 4b shows the random distribution points, there is no rule that proves the data on surface roughness in Table IV does not affected by the control elements have any rules other than cutting mode parameters. Therefore, the relationship between surface roughness and cutting mode parameters presented in formula (4) is very high reliability. This relationship is the basis for the choice of the value of the cutting parameters to satisfy the specific requirements of surface roughness.

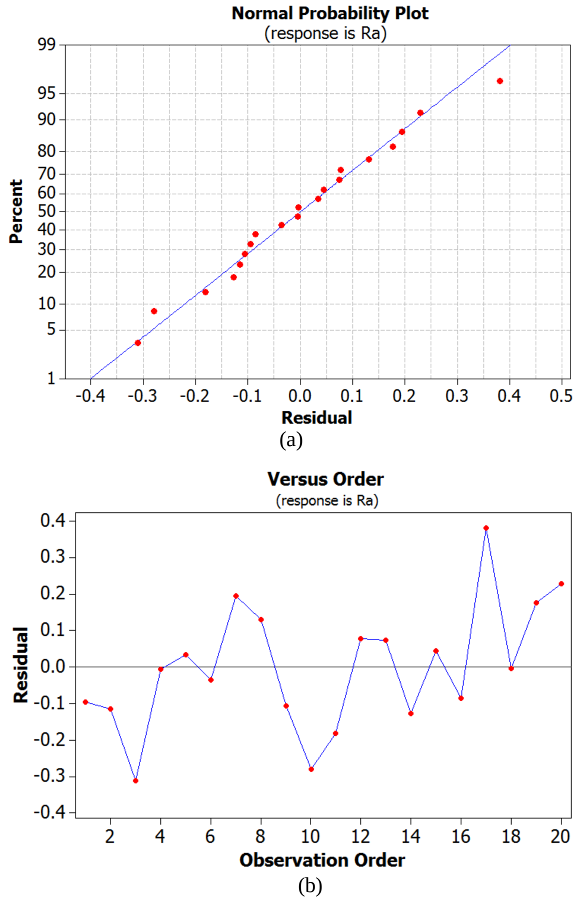


Figure 4. Normal Probability and versus order plot for Ra. a) Normal Probability plot, b) Versus order plot

$$R_a=0.3753+0.0055*v+0.1802*f-0.1725*t-0.0711*v^2 +0.148*f^2+0.0524*t^2-0.0012*v*f-0.082*v*t-0.192*f*t \quad (4)$$

IV. CONCLUSIONS

Twenty experiments were carried out in a matrix of Central composite to investigate the effect of cutting speed, feed rate and depth of cut on the cutting force and surface roughness when milling 40Cr steel with a PVD coated milling cutter. The results are summarized as follows:

The cutting speed has the greatest influence on the cutting force, followed by the influence of the feed rate, the depth of cut has the least influence on the cutting force. As the cutting speed increases and the feed rate, the cutting force decreases. Meanwhile, the value of cutting force will increase if the value of depth of cut increases.

The interaction between the cutting speed and the feed rate has an influence on the cutting force greater than the influence of the interaction between the feed rate and the depth of cut, the interaction between the cutting velocity and the depth of cut has an effect at least to cutting force.

The feed rate has the greatest impact on surface roughness, followed by the extent to which the depth of cut is affected, and the cutting speed has a negligible effect on surface roughness. Increasing the feed rate will increase the surface roughness. Meanwhile, the surface roughness will decrease if the depth of cut increases.

Only the interaction between the feed rate and the depth of cut has a significant effect on surface roughness. The interaction between the cutting speed and the feed rate, the interaction between the cutting speed and the depth of cut have a negligible effect on surface roughness.

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