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An Investigation and Analysis of Cutting Force and Tool Wear in Dry Pocket Milling of Aluminum Alloy Al7075

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Abstract— *This experimental study investigated the effects of milling conditions on the cutting forces and tool wear. The dry pocket milling processes of the aluminum alloy Al7075 were performed to investigate the influence of the cutting conditions on the cutting forces and tool wear. With three controllable factors-three levels (depth of cut, feed rate, and cutting speed), the experimental design with 11 experiments that was selected to carried out. The effect of cutting conditions on the cutting forces and tool wear were analyzed by The ANOVA analysis. In pocket milling process, the most important factor affecting on the cutting forces and tool wear as well was feed rate. The second factor that influenced on the cutting forces and tool wear was depth of cut. The factor that had smallest influence on the cutting forces and tool wear was cutting speed. The most suitable regression of cutting forces and tool wear was a linear regression with the almost confidence level is more than 95 %, and all regression models were successfully verified by experimental results. In additions, the relationship between cutting forces and tool wear was also analyzed. The investigated models of this study can be applied in industrial machining to optimize the anergy comsumption and tool life in dry pocket milling process of the aluminum alloy Al7075.*

Keywords— *Cutting forces, Tool wear, Pocket milling, Dry milling, ANOVA, Al7075.*

I. INTRODUCTION

In the machining processes, in manufacturing industry, milling is one of the most important processes. In the milling process, a reliable quantitative prediction of cutting forces and tool wear is very important to predict the energy consumption, surface quality, geometrical accuracy, tool life, etc.

In recent years, many studies were performed to investigate the influence of cutting conditions on the cutting forces and tool wear to reduce the time and energy consumption of machining processes. The studies focused in the different machining processes such as milling [1, 2], turning [3, 4], etc. In milling processes, the studies about tool wear and cutting forces that were carried out following two directions. In the first direction, cutting forces and tool wear were modeled depending on the physical, chemical, and geometrical phenomena such as friction, temperature, energy consumption in cutting processes, end so on [5-7]. This approach is quite difficult to perform because many factors that affect on the cutting forces and surface roughness. In the second direction, the cutting forces and tool wear were modeled depending on the experimental data. This approach can be applied for specific cases in which only several factors such as cutting speed, feed rate, depth of cut, and so on that were considered in the investigation of their influence on the cutting forces and tool wear [8-12].

In the experimental modelling method, the Artificial Neural Network Methodology was applied to investigate the influence of cutting condition on the cutting forces and tool wear in Milling of Ti-6242S [1]. The influence of cutting parameters and coating materials on the cutting forces and tool wear was studied. The smallest resultant cutting force was obtained by TiN/TiCN/TiAlN multicoated tool [2]. The important machining process parameters that were speed, feed, and rake angle have been chosen and their different levels have been used based on tool-work combination. Cutting force, flank wear and surface finish have been analyzed during machining of Inconel 718 superalloy [3].

The influence of the cutting conditions on the cutting forces and tool wear have been investigated through the response surface methodology (RSM) prediction model [1, 4, 9]. Under various machining conditions, namely dry, preheated, and cryogenic cooling at three different cutting speed, study that was performed focuses on tool-wear behaviour and cutting forces in machining of *NiTi* shape memory [10].

Aluminium alloys as engineering materials that are used extensively in automotive, aerospace, marine and architectural applications because of their high specific strength and corrosion resistance [11]. However, machining of Al and its alloy and finding the suitable tool is really a big challenge because the chips stick to the tool in the machining processes [12. There are many studies that were performed to investigate the influence of cutting conditions on cutting forces and tool wear and determine the optimum values of cutting parameters. However, in points of view, the studies that focused about cutting forces and tool wear when machining the aluminum or aluminum alloy have not been mentioned. The relationship between cutting forces and tool wear was also rarely mentioned.

In this study, the influence of cutting conditions on the cutting forces and tool wear was investigated when dry pocket milling the aluminum alloy Al7075. The main contributions of this study lie in three aspects: (1) Evaluate the effect of cutting conditions on cutting forces and tool wear, (2) Model the cutting forces and tool wear depending on the cutting conditions, and (3) evaluate the relationship between cutting forces and tool wear in pocket milling process.

II. EXPERIMENTAL METHOD

A The Experiment Setup

1. Cutter and workpiece

In order to investigate the effect of machining conditions on the tool wear and surface roughness, a series of pocket milling experiments were performed. The cutter was a flat-end mill HSSCo8 cutter, with number of flutes N = 2, a diameter of 6 mm, cutting edge effective length of 15 mm. The cutter was coated by TiN to achieve the cutter material hardness of 60 HRC.

The workpiece dimensions are 300 mm × 150 mm × 20 mm as shown in Fig. 1. The workpiece material was Aluminum alloy Al7075 and its compositions are listed in Table 1 and the properties of the Al7075 were listed in Table 2.

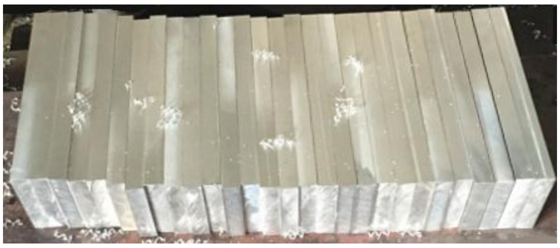


Fig. 1. Experimental workpieces

TABLE 1. Chemical composites of Aluminum alloy Al7075

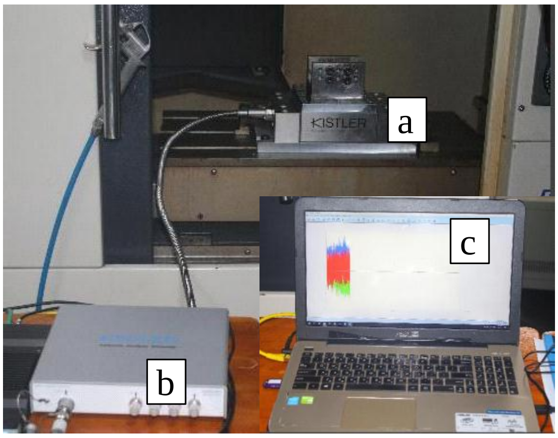
Element	Cu	Mn	Mg	Cr	Zn	Ti	Al
Composite (%)	1,2-2,0	0,3	2,1-2,9	0,18-0,28	5,1-6,1	0,2	balanced

TABLE 2. The properties of Al7075

Properties	Value
Density (kg/m^3)	2,81
Hardness (HB)	150
Young's modulus (N/m^2)	7.20E10
Density (kg/m^3)	2,81
Poisson's ratio	0,33

2 Machine Set-Up and measurement system

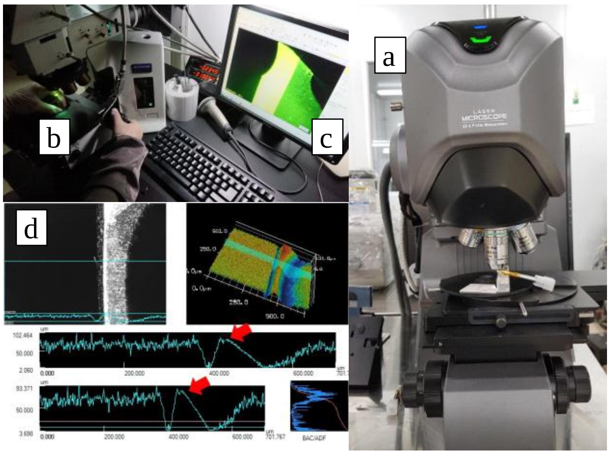
The experiments were performed at a three-axis vertical machining center (HS Super MC500). The spindle speed is in range 100 ÷ 30000 rpm, the maximum feedrate is 48000 mm/min. All experiments were peformed under dry cutting condition. A dynamometer (Kistler Type 9139AA) and processing system were used to measure the cutting forces. The detail is illustrated in Fig. 2.



a. Dynamometer b. Processing system c. PC and Display System

Fig. 2. Setting of cutting force measurement

The flank wear of tool (VB) of the product was measured by Color 3D Laser Microscope Color 3D Laser Microscope VK-X100K/X200 Series system **(**U.S.A**)** as shown in Fig. 3.



a. 3D Laser Microscope b. Cutter

c. Data processing system d. The measured results

Fig. 3. Setting of tool wear measurement

B Experimental Design

In pocket milling process, the axial depth of cut (a), feed rate (F), and the cutting speed (Vc) were selected as the control factors and their levels were listed in the Table 3. In the experimental layout plan, with three factors and three levels, the experimental plan was performed with 11 experiments that was detailed as in Table 4 to analyze the influence of machining parameters on the cutting forces and tool wear.

TABLE 3. Milling parameters and their levels

No.	Machining parameters	Level 1	Level 2	Level 3
1	Axial depth of cut, a (mm)	0.5	1.0	1.5
2	Feed rate, F (mm/flute)	800	1200	1600
3	Cutting speed, V_c (m/min)	188	282	376

III. EXPERIMENTAL RESULTS AND DISCUSIONS

A. Analysis for Cutting Forces

1. Analysis of Variance (ANOVA) for cutting forces

The experimental results were investigated and listed in Table 4. In this study, ANOVA was used to analyze the influence of cutting conditions (axial depth of cut, feed rate, and cutting speed) on the cutting forces and tool wear. This analysis was performed with 95% confidence level and 5% significance level. This indicates that the obtained models are considered to be statistically significant.

The ANOVA results for cutting forces were illustrated in Table 5 in which the contributions of each factor on amplitude of feed force were listed in the last column. The results from Table 5 showed that the most important factor affecting on the cutting forces was feed rate in all directions: 70.75 % for feed

(X) direction, 70.79 % for normal (Y) direction, and 49.51 % for axial (Z) direction. The second factor that influenced on the cutting forces was depth of cut (24.93 % for Fx, 24.51 % for Fy, and 30.27 % for Fz). The third factor that influenced on the cutting forces was cutting speed.

2. Regression and Verification of Cutting Force Models

In this study, four dependent variables are cutting forces (Fx, Fy, Fz), and tool wear, whereas the independent variables are axial depth of cut (a), feed rate (F), and cutting speed (V_c). By using Intercooled Stata 8.2^{TM} software, the most suitable regression of cutting force was a linear regression as given in Eq. 1 to Eq. 3. The R^2 values of the equations obtained by linear regression model for cutting forces were found to be from 92.77 % to 95.43%.

TABLE 4. The experimental design and results

No.	**Code factors**			**Machining parameter**			**Performance measures**			
	X1	**X2**	**X3**	**a (mm)**	**F (mm/min)**	**Vc (m/min)**	**Fx (N)**	**Fy (N)**	**Fz (N)**	**VB (µm)**
1	-1	-1	-1	0.5	800	188	55.74	86.43	51.36	12.523
2	1	-1	-1	1.5	800	188	69.24	109.89	65.31	14.353
3	-1	1	-1	0.5	1600	188	88.61	111.89	87.91	16.433
4	1	1	-1	1.5	1600	188	98.44	150.72	120.82	17.867
5	-1	-1	1	0.5	800	376	52.18	72.50	47.57	11.510
6	1	-1	1	1.5	800	376	66.37	95.27	63.39	14.227
7	-1	1	1	0.5	1600	376	76.39	125.20	54.75	15.327
8	1	1	1	1.5	1600	376	86.01	131.44	81.44	15.593
9	0	0	0	1.0	1200	282	71.36	183.57	76.98	14.235
10	0	0	0	1.0	1200	282	72.57	185.48	76.27	14.597
11	0	0	0	1.0	1200	282	72.61	184.05	76.73	14.530

TABLE 5. Results of ANOVA for cutting forces

ANOVA for Feed Cutting Force (Fx)						
Number of obs: Root MSE:	11 3.25788		R-squared: Adj R-squared:	0.9702 0.9503		
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob > F**	**Percent contribution (%)**
Model	**2070.9718**	**4**	**517.7430**	**48.78**	**0.0001**	
a [mm]	532.2452	2	266.1226	25.07	0.0012	24.93
F [mm/phut]	1510.3001	1	1510.3001	142.30	0.0000	70.75
Vc (m/phut)	28.4258	1	28.4258	2.68	0.1528	1.33
Error	63.6827	6	10.6138			2.98
Total	2134.6538	10	213.4654			100.00
ANOVA for Normal Cuting Force (Fy)						
Number of obs: Root MSE:	11 4.19565		R-squared: Adj R-squared:	0.9805 0.9675		
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob > F**	**Percent contribution (%)**
Model	**5312.0434**	**4**	**1328.0109**	**75.44**	**0.0000**	
a [mm]	1327.9614	2	663.9807	37.72	0.0004	24.51
F [mm/phut]	3835.1282	1	3835.1282	217.86	0.0000	70.79
Vc (m/phut)	148.9538	1	148.9538	8.46	0.0270	2.75
Error	105.6208	6	17.6035			1.95
Total	5417.6642	10	541.7664			100.00
ANOVA for Axial Cutting Force (Fz)						
Number of obs: Root MSE:	11 6.39225		R-squared: Adj R-squared:	0.9401 0.9001		
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob > F**	**Percent contribution (%)**
Model	**3845.8256**	**4**	**961.4564**	**23.53**	**0.0008**	
a [mm]	1238.2245	2	619.1122	15.15	0.0045	30.27
F [mm/phut]	2025.3433	1	2025.3433	49.57	0.0004	49.51
Vc (m/phut)	582.2578	1	582.2578	14.25	0.0092	14.23
Error	245.1655	6	40.8609			5.99
Total	4090.9910	10	409.0991			100.00

Feed force:

$$\left\{\begin{array}{l} Fx = 23.69727 + 15.785 * a + 0.03435 * F - 0.0200532 * Vc \\ \qquad R^2 = 95.43\%, \quad R^2_{Ajd} = 93.47\% \end{array}\right. \qquad (1)$$

Normal force:

$$\left\{\begin{array}{l} Fy = 40.475 + 22.825 * a + 0.0547375 * F - 0.0459043 * Vc \\ \qquad R^2 = 92.77\%, \quad R^2_{Ajd} = 89.67\% \end{array}\right. \qquad (2)$$

Axial force:

$$\left\{\begin{array}{l} Fz = 28.70204 + 24.8425 * a + 0.0397781 * F - 0.090758 * Vc \\ \qquad R^2 = 93.91\%, \quad R^2_{Ajd} = 91.30\% \end{array}\right. \qquad (3)$$

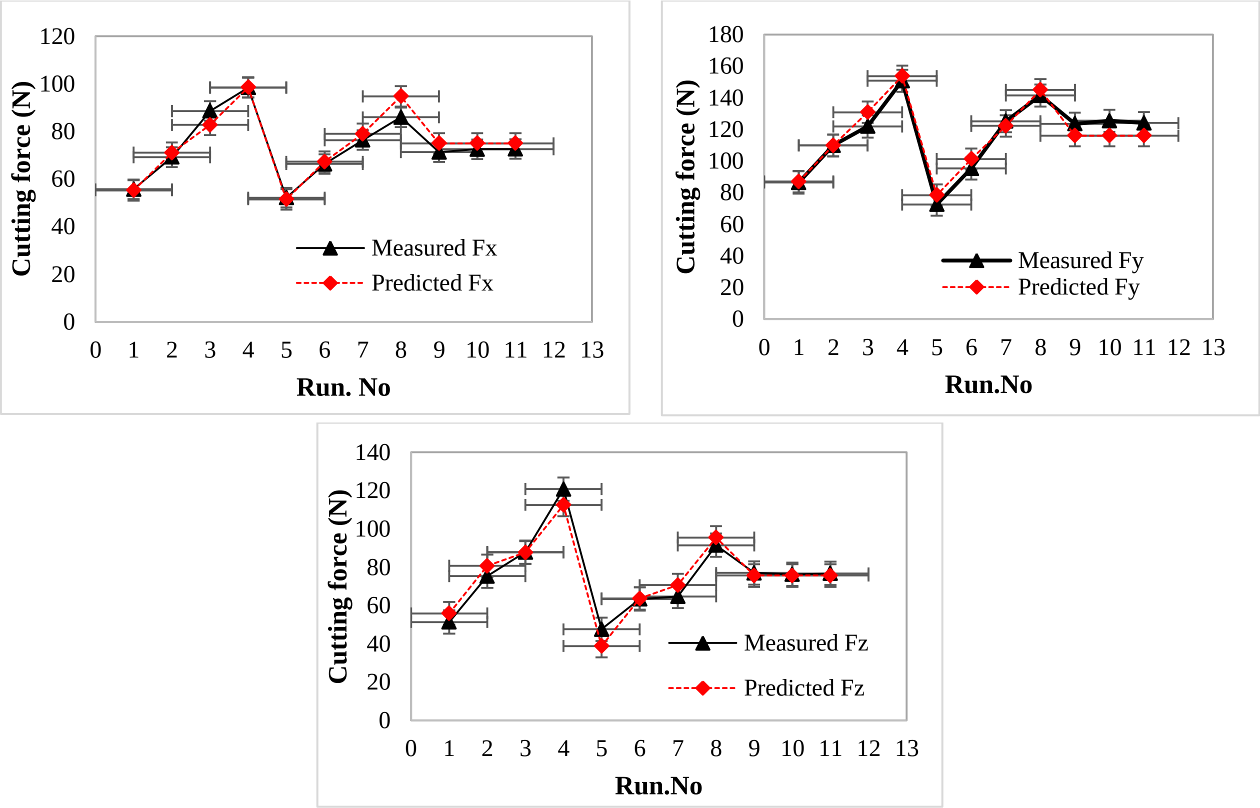


Fig. 4. Measured and predicted results of cutting forces

The verification results of cutting force models were described in Fig. 4. As seen from this figure, in all directions time (feed, normal, and axial directions), the predicted results were very close to the experimental results. There is a very good relation between predicted values and test values. These results showed that the linear regression model was shown to be successfully investigated of cutting forces in pocket milling processes of aluminum alloy Al7075.

B. Analysis for Tool Wear

1. Analysis of Variance (ANOVA) for tool wear

The ANOVA results for tool wear was illustrated in Table 6. The contributions of each factor on the tool wear were listed in the last column. It seems that the most important factor affecting on the tool wear was feed rate (70.71 %). The second factor influencing on the tool wear was axial depth of cut (17.49). And, the third factor influencing on the tool wear was cutting speed (7.56 %).

2. Regression and verification of tool wear models

The most suitable regression of tool wear was a linear regression as given in Eq. 4. The R^2 values of the equations obtained by linear regression model for tool wear were found to be 95.12 %. The compared results of measured values and predicted values of tool wear were described in Fig. 5. It seems that the predicted results were very close to the measured results. These results showed that the linear regression models were shown to be successfully investigated of tool wear in pocket milling processes of aluminum alloy Al7075.

TABLE 6. Results of ANOVA for tool wear

Number of obs:	11		R-squared: 0.9996			
Root MSE:	0.466793		Adj R-squared: 0.9944			
Source	Sum of squares	Degree of freedom	Mean square	F-value	Prob > F	Percent contribution (%)
Model	29.52683	4	7.381708	33.88	0.0003	
a [mm]	5.392005	2	2.696002	12.37	0.0074	17.49
F [mm/phut]	21.80311	1	21.80311	100.06	0.0001	70.71
Vc (m/phut)	2.331704	1	2.331704	10.7	0.017	7.56
Error	1.307372	6	0.217895			4.24
Total	30.83419	10	3.083419			100.00
ANOVA for tool wear after 180 minutes machining						

$$\begin{cases} VB = 9.727522 + 1.61175 * a + 0.0041272 * F - 0.0057434 * Vc \\ R^2 = 95.12\%, \quad R^2_{Ajd} = 93.03\% \end{cases} \qquad (4)$$

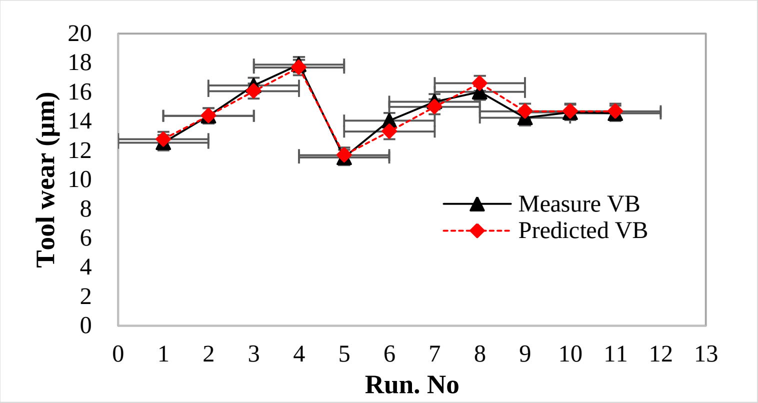


Fig. 5. Measured and predicted results of tool wear

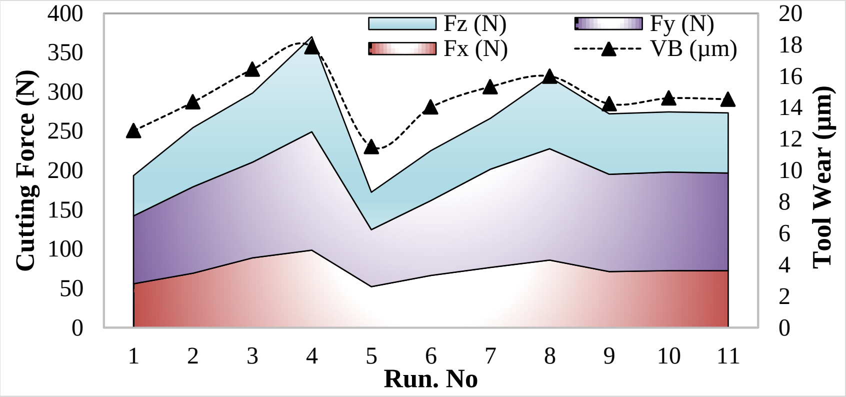


Fig. 6. Relationship between cutting forces and tool wear

C. The Relationship between Tool Wear and Surface Roughness in Milling

In this paper, the relationship between cutting forces and tool wear was also investigated and drawn in one diagram as shown in Fig. 6. It seens that the tendency of the tool wear is the same that one of the cutting force in all directions. As seen from this figure, if the tool wear increased, the cutting forces also increased and if the tool wear decreased, the cutting forces also decreased. These can be explained that in machining process, when the tool wear changes, the geometry of the cutting tool also changes, and then, the geometry of the chip also changed, this thing made the cutting forces changing.

IV. CONCLUSIONS

In this study, an experimental method was conducted to investigate the influence of cutting conditions on the cutting forces and and tool wear. Depending on the analyzed results, the conclusions of this study can be drawn as follows.

1. The most important factor affecting on the cutting forces and tool wear was feed rate. The second factor that influenced on the cutting forces and tool wear was depth of cut, while the third factor that influenced on the cutting forces and tool wear was cutting speed.

2. The most suitable regression of the cutting forces and tool wear a linear regression. The R^2 values of the equations obtained by linear regression models were found to be from 92.77 % to 95.43 %. All regression models were successfully verified by experimental results.

3. The tendency of the tool wear is the same that one of the cutting force in all directions. If the tool wear increased, the cutting forces increased and if the tool wear decreased, the cutting forces also decreased.

Cutting force and tool wear models can be used to optimize the machining surface and reduce the tool wear, and will be the extended researches.

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