Experimental Studies to Verify the Effect of Chip Shrinkage Coefficient on Cutting Forces and Surface Roughness in High Speed Milling of A6061 Aluminum Alloy

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Received: June 14, 2016; accepted: June 9, 2017

Abstract

This paper studied the relationship between the cutting force, surface roughness and chip shrinkage coefficient through the affect of cutting parameters, i.e., cutting speed, feed rate and uncut chip thickness. Experimental results of the chip shrinkage coefficient, cutting force and surface roughness at various cutting parameter values for high-speed milling of A6061 aluminum alloy were presented in this study. The results show that the cutting force and surface roughness can be derived based on the relationships with chip shrinkage coefficient.

Keywords: High-speed milling, A6061 aluminum alloy, Chip shrinkage coefficient, Surface roughness, Cutting force.

1. Introduction

High-speed milling (HSM) has become an innovative technique, which keeps improving progressively. It is particular important to model of the HSM process in order to aid for prediction of the cutting process variables. Consequently, modeling of HSM process is essential for the design and optimization of the cutting conditions.

Cutting force in a milling process is one of the most important issues for the selection of machining parameters, such as feed rate and spindle speed [1]. Many researchers using both experiment and simulation approaches for prediction of cutting forces of HSM processes [2-4]. Compare to experiment approach, simulation of a milling process using Finite Element Method (FEM) show a beneficial of providing more detail information of cutting process variables, such as cutting forces, tool stresses and temperatures [5]. Nowadays, development of cutting force model for HSM is increasing interests toward higher precise cutting force estimation and applicable for different cutting conditions.

One of the major challenges of milling at high speeds is that high-speed milling leads to the high temperature and stress growing at the interfaces of chip-tool or workpiece-tool resulting in unexpected roughness of workpiece surface finish [6]. In order to ensure workpiece surface roughness at a desired quality, properly cutting parameters should be established. Several researchers studied the relationships of surface roughness and cutting parameters such as nose radius, clearance angle, cutting speed, feed rate, depth of cut, rake angle [7]. Nowadays, research on surface roughness influenced by cutting parameters is continuing for enhancing product quality at low cost.

Another concern in modeling the HSM process is estimation of chip geometric parameters, such as chip thickness, chip length, etc. Since accuracy of the model for chip parameter estimation directly affects the accuracy of the cutting force predictions, accurate chip modeling is always desired in the estimation of cutting forces, especially in micro milling [8]. Chip shrinkage coefficient defined as the ratio of the uncut chip length by the actual chip length, can be a prominent parameter for modeling of a cutting process. However, studies on the chip shrinkage coefficient have been limited in literature.

This study investigate the effect of cutting parameters, i.e., cutting speed, feed rate and uncut chip thickness on the chip shrinkage coefficient, cutting force, surface roughness. The relationship between this factor are found the chip shrinkage coefficient and cutting force, surface roughness and cutting parameters are found through experimental measurement for high-speed milling of A6061 aluminum alloy.

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2. Experimental setup

2.1 Workpiece material

The workpiece used in this study is aluminum alloy A6061, which has the hardness of 97HB. The chemical composition of workpiece material is represented in Table 1. Several workpieces used for experiment are shown Figure 1. The workpiece dimensions are 70x30x70 (mm).

Table 1. Chemical composition of the workpiece material (%).

Si	Fe	Cu	Mn	Mg
0,4-0,8	0,3	0,05-0,3	0,10	0,8-1,2
Cr	Zn	Ti	Al	
0,05-0,30	0,25	0,15	remaining	

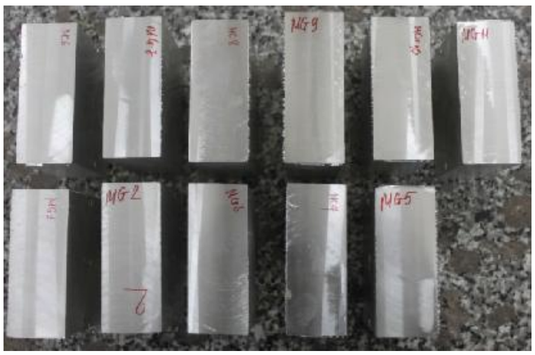

Fig .1. The workpieces used in experiments

2.2 Milling experiment

All the experiments are performed on a HS Super MC500 high-speed milling machine maximum feed rate of 30 m/min, maximum spindle speed of 30.000 rpm, travel distances of the operating platform in the X, Y and Z directions of 500 mm, 400 mm and 300 mm, respectively. Dry milling condition with carbide insert cutting tool (APMTT1604PDTR TC300) and diameter of 40 mm is used for milling.

2.3 Measurement equipment

The cutting forces are measured by force measurement device Kisler, which is equipped with a force sensor (Kisler 9257B). The maximum load capacities of the device in X, Y and Z directions are 1500N, 1500N and 5000N, respectively. The sensitivity of sensor in X, Y and Z directions are 7.39 pC/N 7.39 pC/N and 3.72 pC/N, respectively. The measured data is collected by an acquisition system using DASYlab 10.0 software.

The surface roughness of the machined workpiece is measured by a surface roughness tester (Mitutoyo SJ–400). The roughness values are in µm. Figure 2 shows the surface roughness measuring device.

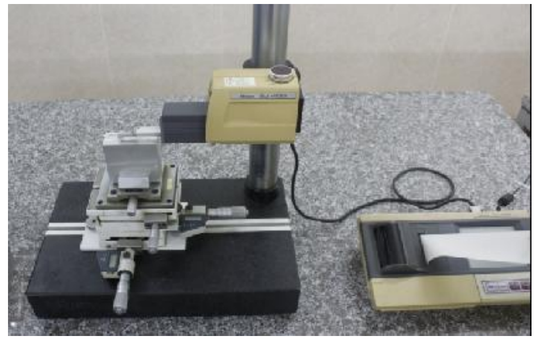

Fig. 2. Surface roughness tester

The Sartorius Volume Comparator (S224-1S) scale is used to determine the weigh of the chip after cutting. The scale parameters are as follows: capactiy of 220 gr, readability of 0.1 mg.

The chip shrinkage coefficient (K) can be calculated by following formula [11]:

$$K = \frac{1000.Q}{\rho .L.S.t} \qquad (1)$$

where Q is weight of the chip (gr), ρ is material density (g/cm^3), l is chip length (mm), S and t are feed rate (mm/rev) and uncut chip thickness (mm), respectively.

3. Design of experiment

The effects of cutting speed, feed rate, uncut chip thickness, on chip shrinkage coefficient, force cutting, surface roughness are examined using a three-factor/three-level full factorial design [10]. The range of each factor is set at three different levels as shown in Table 2. Figure 3 shows the experimental set-up of the milling process.

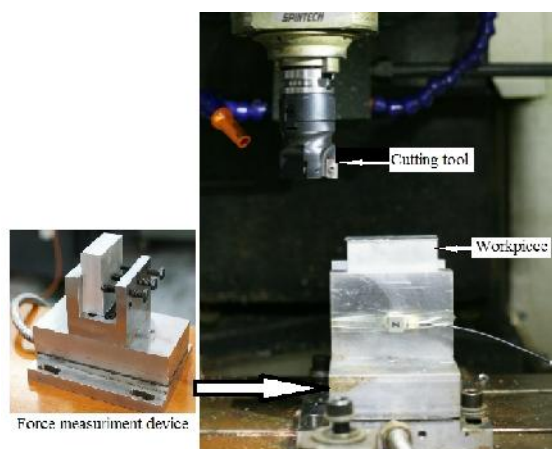

Fig. 3. Experimental set-up

Table 2. Cutting parameters for the experiment

No.	Parameter	Unit	Level 1	Level 2	Level 3
1	*V* *(cutting speed)*	m/min	1000	1130	1256
2	*f* *(feed rate)*	mm/min	800	1350	1800
3	*t* *(uncut chip thickness)*	mm	0,5	1,0	1,5

Table 3. Experimental results

No	V (m/ min)	f (m/min)	t (mm)	K	F (N)	Ra (µm)
1	1000	800	0,5	1,294	135,71	0,64
2	1256	800	0,5	1,304	126,98	0,39
3	1000	1800	0,5	1,322	120,88	0,60
4	1256	1800	0,5	1,370	111,73	0,31
5	1000	800	1,5	1,144	146,36	0,53
6	1256	800	1,5	1,102	128,42	0,48
7	1000	1800	1,5	1,137	139,71	0,55
8	1256	1800	1,5	1,133	117,38	0,35
9	1130	1350	1	1,236	125,46	0,44
10	1130	1350	1	1,236	124,82	0,44
11	1130	1350	1	1,236	126,72	0,44

4. Results and discussions

4.1 Influences of V, f and t on the K, F and R_a

Table 3 shows the experiment results of *K, F,* R_a as a function of *V, f* and *t*. Using curve-fitting tool, the relationship between *K, F,* R_a dependence on *V, f* and *t* is established. That relationship is described by the following equation (2), (3),(4).

$$K = a_1 V^{a_2} f^{a_3} t^{a_4} \quad (2)$$

$$F = b_1 V^{b_2} f^{b_3} t^{b_4} \quad (3)$$

$$R_a = c_1 V^{c_2} f^{c_3} t^{c_4} \quad (4)$$

where a_i, b_i, c_i (i = 1...4) are the constants to be determined. Using curve fitting tool in Minitab17, those constants can be determined as shown in Table 4.

Table 4. Fitted constants obtained by surface fitting method

i	1	2	3	4
a	0,889866	0,0090714	0,0339467	-0,1402635
b	1264,012	-0,36893	0,047466	0,092838
c	5820,781	-1,378843	0,04978739	0,10138765

Figures 4-6 show *K*, *F*, and R_a as a function of the cutting parameters, i.e., *V*, *f* and *t*, respectively, obtained using equations (2), (3) and (4) with the constants in Table 4. Figure 4 shows that increasing cutting speed leads to the increase of *K*. On the other hand, *K* is decreased with increasing depth of cut. This figure also shows that *t* has a great influence on *K*, while the effect of *f* on *K* is minor. Besides, cutting speed increases leading to the decrease in contact area between the chip and the front of the tool. Consequently, chip shrinkage coefficient is increased [11]. In order to obtain the optimal cutting parameter values for minimizing *K*, MAPLE software is utilized based on NLPSolve command. Optimal values for *V*, *f* and *t* are 1000 m/min, 800 mm/min, and 1.5 mm, respectively.

From Figure 5, increasing *V*, *f* or *t* all reduces *F*. This is because at high-speed cutting, the generated heat can soften the materials thus decreasing cutting forces [11]. Using NLPSolve command, the optimal parameters of *V, f* and *t* for the objective function of minimizing *F* are also found equal to 1256 m/min, 1800 mm/min, and 0.5 mm, respectively.

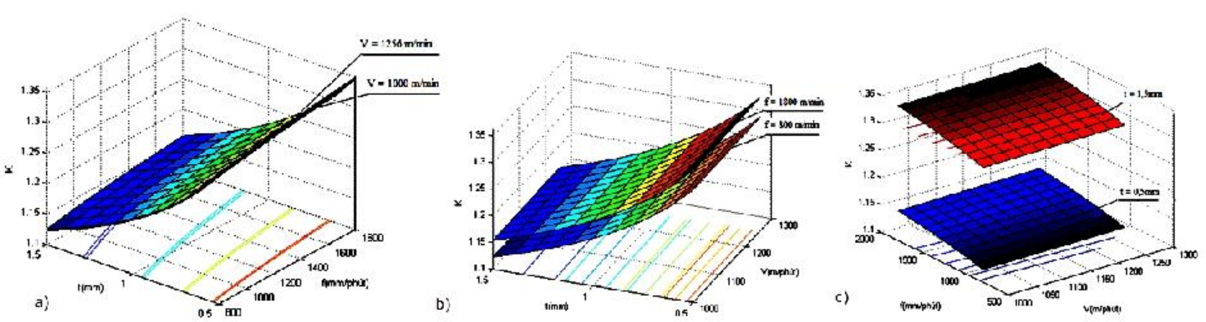

Fig. 4. The relationship between *K* and cutting parameters *V, t* and *f.* a) Fixed *V*, b) Fixed *f*, c) Fixed *t*

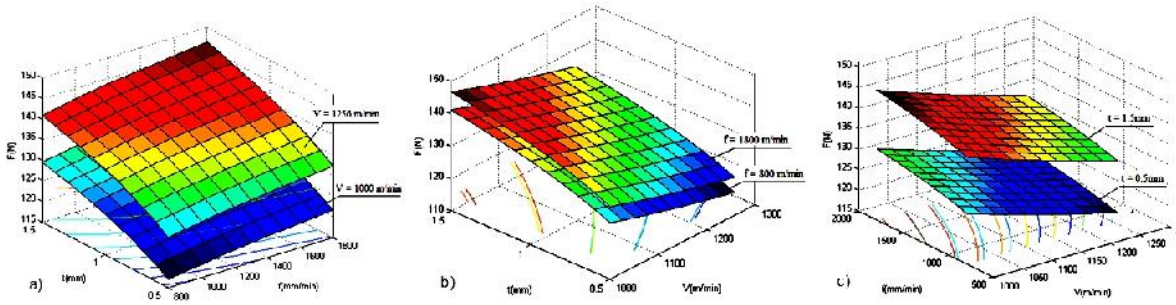

Fig. 5. The relationship between F and cutting parameters V, t and f. a) Fixed V, b) Fixed f, c) Fixed

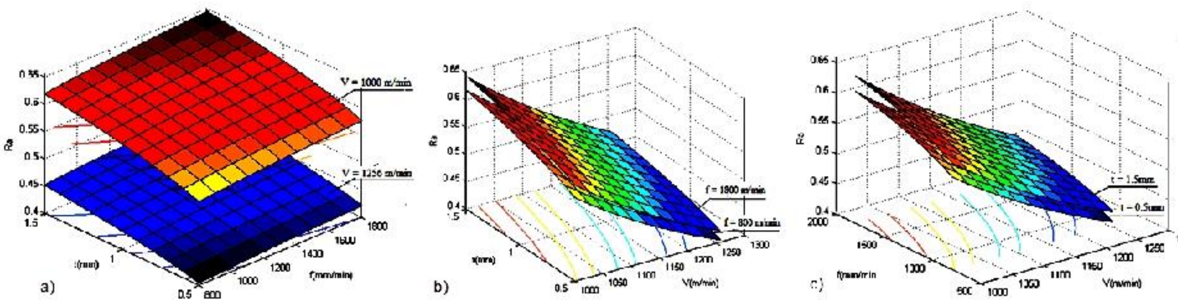

Fig. 6. The relationship between R_a and cutting parameters V, t and f. a) Fixed V, b) Fixed f, c) Fixed t

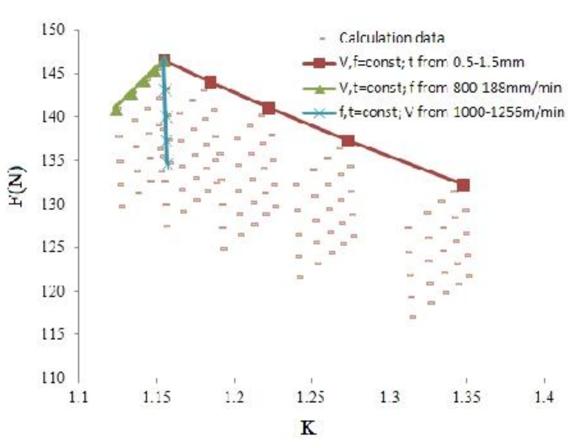

Fig. 7. The relationship between F and K

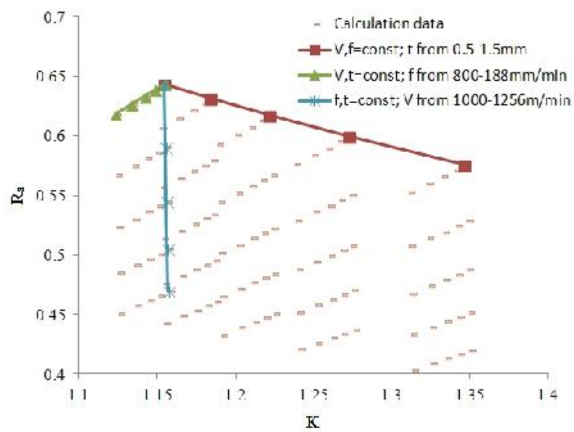

Fig. 8. The relationship between R_a and K

Figure 6 indicates that R_a increases with increasing f and t but reduces with increasing V. This is because under high-speed cutting, the built up edge phenomenon would disappears leading the reduction of surface roughness [11]. Similar to K and F, the optimized values of V, f and t for minimizing R_a are 1256 m/min, 1800 mm/min and 0.5 mm, respectively.

4.2 *The relationship between F and K, R_a and K*

This section analyzes the relationship between F and K as well as, R_a and K based on Eqs. (2-4). By eliminating V, f and t from Eqs. (2-4), the relationship between F and K, R_a and K are found. As shown in Figures 7-8, In order to verify the effect of various V, f *and* t on the relationship between F and K as well as R_a and K, the five-level full factorial design was assigned for cutting speed (V) of 1000, 1064, 1128, 1192, 1256 m/min; feed rate (f) of 800, 1050, 1300, 1550, 1800 mm/min and uncut chip thickness (t) of 0.5, 0.75, 1.00, 1.25, 1.50 mm, respectively.

It is seen that minimum values of F and R_a are 117N and 0.403μm, respectively, which are all obtained at K = 1.312. When K is equal to 1.154, maximum values of F and R_a are obtained equal to 146N and 0.64μm, respectively.

The figures 7 and 8 also summarize the affected trend of cutting parameters i.e., cutting speed, feed rate and uncut chip thickness on the cutting force (F) and surface roughness (Ra) related with chip shrinkage coefficient (K) as discussing in detail on section 4.1. From those figures, the optimal cutting parameters can be obtained by minimizing cutting force (F), surface roughness (Ra) and chip shrinkage coefficient (K). In order to minimize the F and R_a, the maximum of cutting speed (*V*) and minimum of feed rate (*f*) also uncut chip thickness (*t*) should be set. However, the decreasing of uncut chip thickness (*t*) will increase the chip shrinkage coefficient (K) therefore (*t*) will be chosen based on the productivity of manufacturing process.

5. Conclusions

This paper presents an experimental study on relationship between cutting force, surface roughness and chip shrinkage coefficient when high speed milling of A6061 aluminum alloy. Some conclusions are given as follows:

1. The relationship between the cutting force, surface roughness and chip shrinkage coefficient through cutting parameters e.g., cutting speed, feed rate, uncut chip thickness are explicitly described by mathematical functions.

2. The optimal cutting parameters for chip shrinkage coefficient, cutting force and surface roughness can be found by maximizing the cutting speed (V) and minimizing the feed rate (f), which are useful for practical milling of A6061 aluminum alloy.

Acknowledgements: This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number “107.02-2016.01”.

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