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Statistical investigation on burrs thickness during milling of 6061-T6 aluminium alloy

S. A. Niknam, V. Songmene
Department of Mechanical Engineering, École de TechnologieSupérieure (ÉTS)
1100 Notre-Dame west street, Montréal, Québec, H3C 1K3, Canada
Email:seyed-ali.niknam.1@ens.etsmtl.ca, victor.songmene@etsmtl.ca

Abstract: Burr formation is a research topic with high relevance to industrial applications. According to deburring perspective, the thickness of the burr is of interest as it describes the time and method necessary for deburring of the machined part. Burr thickness (B_t) measurements are costly and non-value-added operations which in most of the cases require the use of Scanning Electron Microscope (SEM) for accurate burr characterization. This study presents an experimental study to evaluate parameters affecting the burr thickness and to search for correlation between the cutting parameters and the burr thickness. Amongst investigated burrs, exit up milling side burr is found to be highly controlled with machining parameters. It has shown a high correlation rate with tangential force (F_t). Linear first order mathematical models are developed to predict exit up milling side burr thickness and F_t as a function of feed per tooth and depth of cut.

Keywords: Dry milling, burr formation, burr thickness, cutting parameters, aluminium.

1. INTRODUCTION

Burrs formed during machining are defined as projections of materials beyond workpiece limits, and which have significant impact on machining economics. They must thus be removed in subsequent finishing operations. As pointed out by [Gillespie., 1999], deburring and edge finishing on precision components may represent as much as 30 percent of the cost of finished parts. To decrease deburring costs, it is necessary to select the mostly desirable deburring methods, in addition to identifying effective burr formation process parameters. [Gillespie., 1996] was among the first persons who described different types of machining burrs as follows: Poisson burr, Rollover burr, Tears burr and Cut-off burr. Burr formation in aluminium alloy during orthogonal cutting was investigated by [Hashimura et al., 1995]. All burrs in this study are negative burrs. [Shefelbine et al., 2004] studied the influence of tool wear and coolant on burr size in face milling of cast iron and aluminium alloys. The study conducted by [Olvera et al., 1996] on face milling of medium carbon steel AISI 1040 shows that exit angle and depth of cut are the influencing cutting parameters on exit burr in the cutting direction, whereas depth of cut could be the main factor affecting exit burr in feed direction. In [Chen et al., 2001], milling burr formation were predicted and minimized for slot and face milling using strategies of tool path planning, processing parameter optimization as well as workpiece rigidity strengthening. To the authors' knowledge, very low volume of information is available about dominant process parameters on slot milling burrs in ductile materials such as wrought aluminium alloys. Furthermore, most of existing research works in literature aim to characterise the burr height, while from a deburring perspective, the thickness of the burr is of interest because it describes the time and method necessary for deburring a workpiece [Aurich et al., 2009]. In addition, only few studies used statistical analysis to precisely determine the dominant process parameters on burrs size [Lauderbaugh., 2009; Lekkala et al., 2011].

The main objective of this work is to evaluate the optimum process parameters on burrs thickness in top down milling side, exit up milling side, top up milling side and exit bottom side using statistical techniques. The relative importance of process parameters on responses is identified using analysis of variance (ANOVA). Linear mathematical models are then developed to predict controllable burrs thickness and cutting force, as a function of cutting parameters, when using different tools.

2. EXPERIMENTAL PROCEDURE

The plates of aluminum alloys 6061-T6 with dimensions of 38× 12×12 mm were used for the milling tests. A multi-level full factorial design (3^3×2) was used as a design of experiment. The experimental factors and their levels are shown in Table 1. In total, 54 experiments are necessary to complete the study. Slot milling tests were conducted using a 3-axis CNC machine tool (Power: 50kW, Speed: 28000 rpm; torque: 50 Nm). Cutting forces were measured using a 3-axis dynamometer (Kistler-9255B) with a sampling frequency of 1000 Hz. Tangential forces (F_t) were measured through cutting force signals extracted in each trial. An optical microscope, equipped with high resolution camera was used for recording the burrs images. The burr size measurements were conducted on recorded images. An average of four burr thickness readings was taken as the burr size in this study.

Table 1; Cutting parameters and their levels

Experimental parameters		Level		
		1	2	3
	Insert Ref	IC 328	IC 908	IC 4050
A: Tool	*Coating*	TiCN	TiAlN	TiCN+Al_2O_3+TiN
	Insert nose radius, Rε, (mm)	0.5	0.83	0.5
B: Depth of cut (mm)		1	-	2
C: Feed per tooth (mm/z)		0.01	0.055	0.1
D: Cutting speed (m/min)		300	750	1200

3. METHOD OF ANALYSIS

In analysing the quality index parameters in machined parts (e.g. burr thickness, surface roughness), statistical models play an important role [Kilickap., 2010].The following statistical terms are used in this article for statistical analysis using STATGRAPHICS Centurion XV:

- Pareto analysis: A Pareto chart compares the relative importance and statistical significance of the main and interaction effects between process parameters. This chart identifies influential factors in order of decreasing contribution.
- Main effect plot: The Analysis of means (ANOM) is used to determine the optimal process parametric settings by estimating the main effect of each parameter, which is presented in the main effect plot diagram [Phadke., 1989].
- ANOVA: The analysis of variance (ANOVA) allows an examination of the main effects of independent variables and their interactive effects to determine their combined effects on the response.
- Response surface methodology (RSM): RSM is useful for modelling, analysing, developing and optimising engineering problems.

4. RESULT AND DISCUSSION

4.1. Milling burrs

The slot milling burrs are presented in Figure 1, followed by investigated burrs in this study as shown in Figure 2. Three design models are used to statistically analyse the influence of process parameters on measured thickness of presented burrs. By considering the statistical R^2 and Adj. R^2 of design models for each burr in Table 2, it is evident that variation of $B_{t,1}$ is more dependent to cutting parameters as compared to other burrs. The results in Table 2 exhibit that $B_{t,2}$, $B_{t,4}$ and $B_{t,8}$ are not dominated by cutting process parameters. Therefore, they will not be studied in further details in this article.

List	**Burr name**
B_1	Exit up milling side
B_2	Exit bottom burr
B_3	Exit down milling side burr
B_4	Top down milling burr
B_5	Down milling entrance burr
B_6	Entrance bottom burr
B_7	Up milling entrance burr
B_8	Top up milling burr

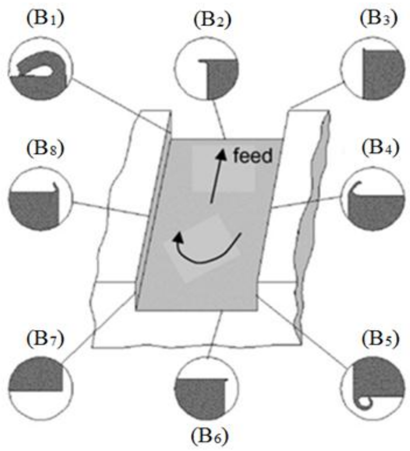
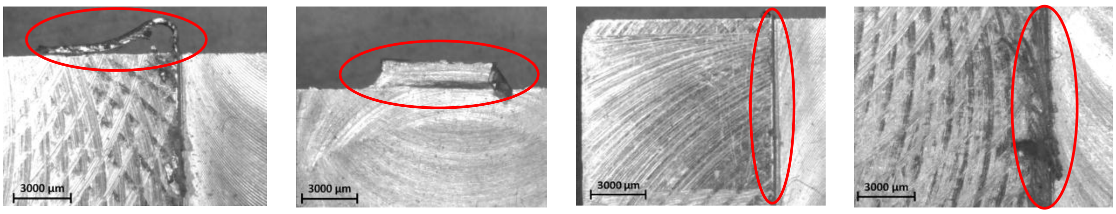


Figure 1; slot milling burrs



(a) Exit up milling side burr (b) Exit bottom burr (c) Top down milling burr (d)Top up milling burr

Figure 2; Investigated slot milling burrs

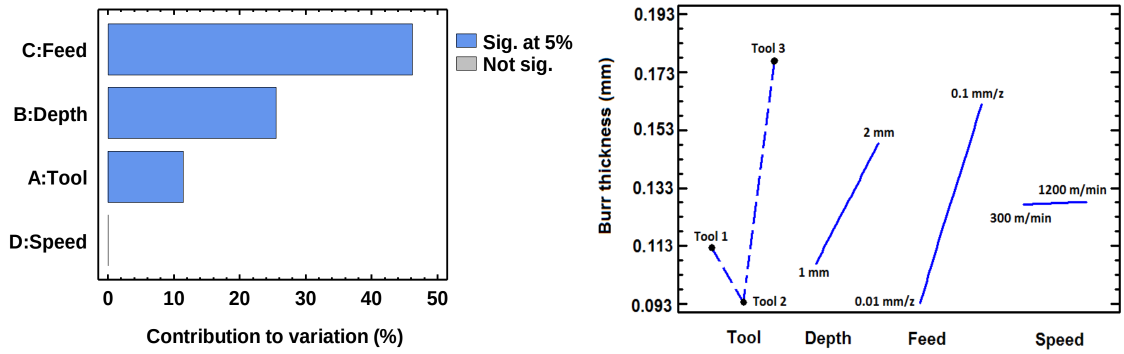
The non-considerable difference between R^2 and Adj. R^2 in linear and quadratic models in $B_{t,1}$ determines that the interactive effects between process parameters on variation of $B_{t,1}$ is 9.1%. In addition, a P-value of 0 in each three models indicates that the models are adequate (see Table.2). Then linear model of $B_{t,1}$ will be used for further investigations.

Table 2; Model summary statistics for milling burrs thickness at different locations

No.	Milling Burr thickness	Design Model	R^2 %	Adj. R^2 %	F-ratio	P value
1	Exit up milling side burr thickness ($B_{t,1}$)	Linear	**83.1**	**81.3**	**47.5**	**0**
		2-Factor Interactions	**90.3**	**86.8**	**25.9**	**0**
		Quadratic	**92.2**	**88.9**	**27.5**	**0**
2	Exit bottom burr thickness ($B_{t,2}$)	Linear	22.9	14.91	2.85	0.024
		2-Factor Interactions	40.0	18.54	1.86	0.063
		Quadratic	46.1	22.79	1.97	0.043
3	Top Down milling burr thickness ($B_{t,4}$)	Linear	14	5.04	1.56	0.186
		2-Factor Interactions	26.1	0	0.99	0.482
		Quadratic	28.1	0	0.90	0.575
4	Top up milling burr thickness ($B_{t,8}$)	Linear	19.8	11.51	2.38	0.052
		2-Factor Interactions	39.6	17.91	1.82	0.069
		Quadratic	46.9	23.95	2.04	0.036

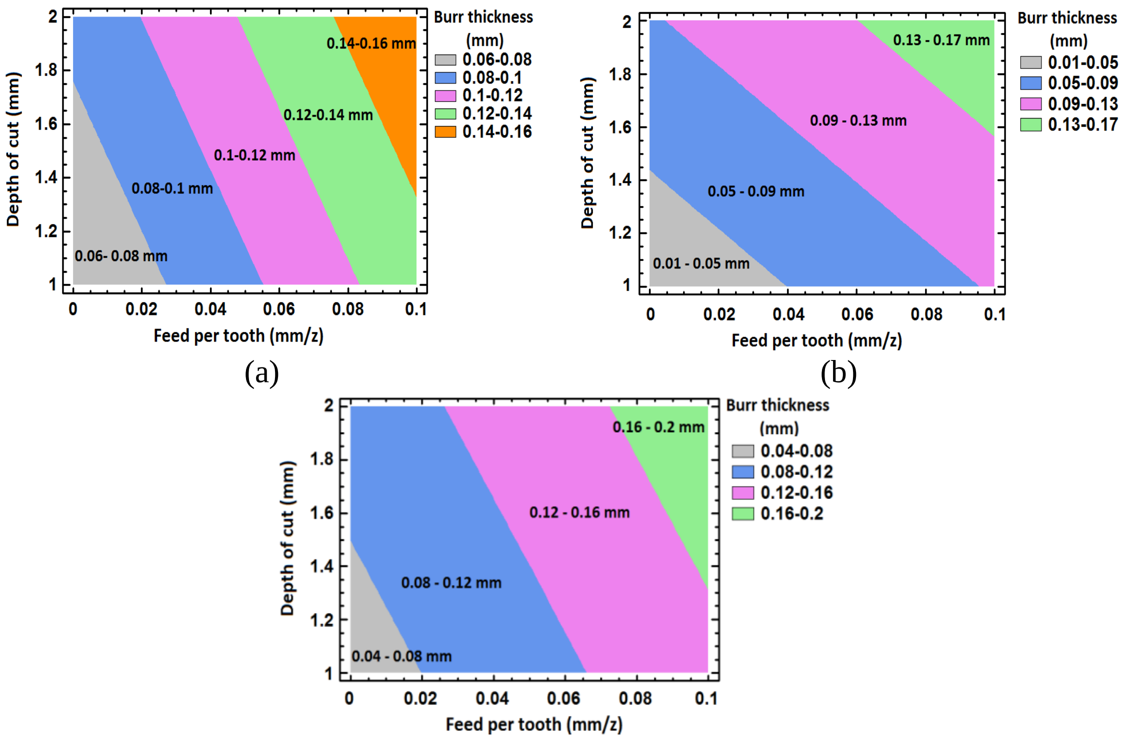
4.2. Analysis of exit up milling side burr

The relative contribution of milling parameters (Pareto chart) and direct effect plot with respect to $B_{t,1}$ in linear design model are shown in Figures 3(a) and 3(b), respectively. From Figure 3(a), depth of cut, feed per tooth and tool are the cutting parameters with the most contribution to variation of $B_{t,1}$ in Al 6061-T6. From Figures 4(a-c), it is observed that at higher values of feed per tooth and depth of cut, the $B_{t,1}$ increases at fixed cutting speed 1200, when cutting tools 1-3 are used, respectively. By assessing these plots, it could be inferred that , regardless the effect of feed per tooth, depth of cut and cutting speed, $B_{t,1}$ decreases when cutting tool 2 with insert nose radius (Rε) 0.83 mm is used. In metal cutting, feed rate, depth of cut and cutting speed are the main controlling parameters [Korkut et al., 2007].The first considerations of burr formation in metal cutting came along with investigations about chip formation as burr formation mechanism highly depends on chip formation mechanism. In milling operation, the instantaneous chip thickness, $h(\varphi)$, varies periodically as a function of time-varying immersion angle ,φ, which largely varies tangential force ,$F_t(\varphi)$, and radial force, $F_r(\varphi)$, in milling operations (see Figure.5). In slot milling, the magnitude of F_t is greater than F_r when tool leaves the workpiece (see Figure.5). Therefore it is believed that burr formation at exit up milling side is mainly caused by F_t.



(a) (b)

Figure 3;(a) Pareto chart for $B_{t,1}$ in linear design model, (b) Direct effect plot for $B_{t,1}$



(a) (b) (c)

Figure 4; 2D contour plot of $B_{t,1}$ as function of feed per tooth and depth of cut at fixed cutting speed 1200 (m/min) when using :(a)Tool 1, (b) Tool 2, (c) Tool 3

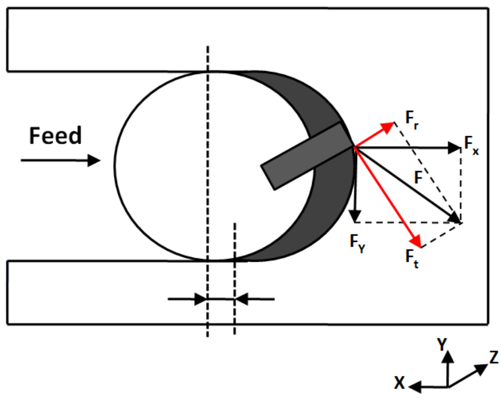


Figure 5; Slot milling under orthogonal cutting conditions

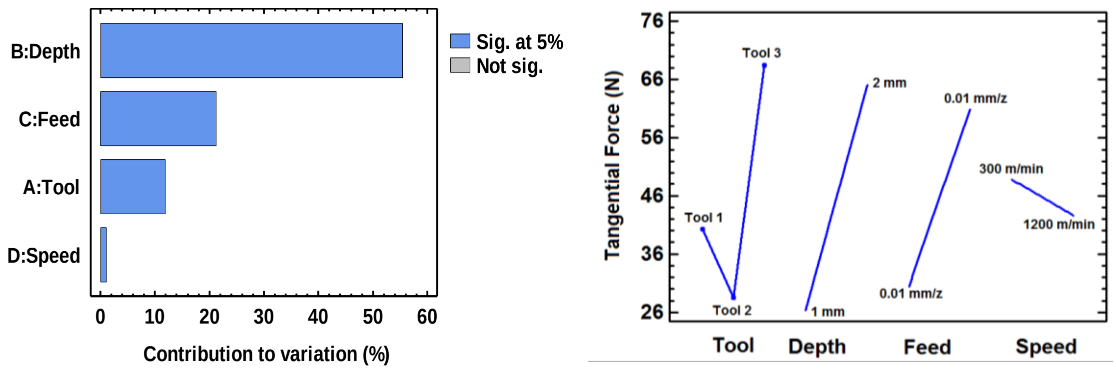
4.3. Cutting force

The ANOVA is applied to study the effect of cutting parameters on recorded F_t in each trial as presented in Table 3. Statistical design models in Table 3 show that variation of F_t is mainly affected by cutting parameters. As similar to $B_{t,1}$, design models in Table 3 indicate that the difference between R^2 and Adj. R^2 in linear and quadratic models is about 9%. In addition, P-value of 0 in each three models indicates their adequacy (see Table.3). Therefore, to avoid of difficulties on developing RSM prediction models, linear design model of F_t will be used for further investigations. The relative contribution of milling parameters (Pareto chart) and direct effect plot with respect to F_t in linear design model are shown in Figures 6(a) and 6(b), respectively. From Figure 6(a), depth of cut and feed per tooth are the cutting parameters with the most contribution on F_t. Figure 6(b) exhibits that an increase in feed per tooth and depth of cut increases F_t. This is due to direct effects of these two parameters on chip thickness which largely affects directional cutting forces. The cutting speed and tool have least significant effect on variation of F_t as compared with feed per tooth and depth of cut. Figures 3(b) and 6(b) exhibit that an increase in insert nose radius leads into smaller F_t and $B_{t,1}$.

Table 3; Model summary statistics for F_t

No.	Design models	R^2 %	Adj. R^2 %	F-ratio	P value
1	Linear	89.43	88.34	81.29	0
2	2-Factor Interactions	97.39	96.45	104.04	0
3	Quadratic	97.83	96.89	104.34	0

Exponential design model is found as the best fitted model for F_t and $B_{t,1}$ with 86.26% correlation coefficient (see Figure 7), followed by multiplicative and linear models with correlation coefficients of 84.41% and 79.89%, respectively.



(a) (b)

Figure 6; (a) Pareto chart F_t in linear design model, (b) Direct effect plot for F_t

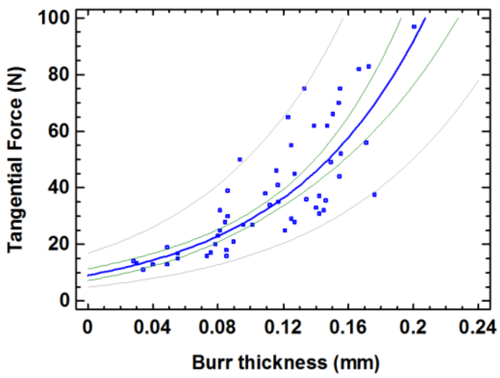


Figure 7; Exponential regression model between F_t and $B_{t,1}$

4.4. RSM-Based modelling

Linear first order mathematical models (Eqs.1-6) are developed to predict F_t and $B_{t,1}$ as a function depth of cut and feed per tooth, when cutting tests were performed using various cutting tools:

Burr thickness

$B_{t,1}$ (Tool 1) = -0.035 + 0.71× f_t + 0.025×a_c R^2 = 91.73% (1)

$B_{t,1}$ (Tool 2) = -0.043 + 0.71× f_t + 0.065×a_c R^2 = 91.96% (2)

$B_{t,1}$ (Tool 3) = 0.028+ 0.86× f_t + 0.034×a_c R^2 = 85.95% (3)

Cutting forces

F_t (Tool 1) = -47.65 –534.722× f_t + 50.33× a_c R^2 = 93.42% (4)

F_t (Tool 2) = -15.16 +156.5× f_t + 23.38× a_c R^2 = 87.95% (5)

F_t (Tool 3) = -31.18 + 340.74× f_t +38.77× a_c R^2 = 91.58% (6)

Where, f_t is feed per tooth and a_c is depth of cut.

5. CONCLUSION

The burr thickness in exit up milling side, exit bottom, top down and top up sides in slot milling of aluminium alloys 6061-T6 were investigated using a multi-level factorial design of experiment. Statistical methods were then used to evaluate the dominant process parameters on variation of four types of milling burrs thickness. According to experimental and statistical results, the following conclusions were drawn:

- The exit burr thickness in up milling side ($B_{t,1}$) of machined parts is statistically sensitive to variation of cutting parameters in slot milling, as compared with top up/down and exit bottom burrs.
- The measured tangential forces (F_t) have very good correlation with measured $B_{t,1}$. They both can be controlled by variation in feed per tooth and depth of cut. In addition, machining tests with larger insert nose radius resulted in smaller force and burr thickness.
- An increase in cutting speed, leads into a decrease in F_t and increase in $B_{t,1}$, respectively. However according to statistical analysis, cutting speed had the least significant effect on variation of F_t and $B_{t,1}$ than other cutting parameters. Therefore, linear mathematical models for prediction of F_t and $B_{t,1}$ were presented as a function of feed per tooth and depth of cut, when cutting tests were performed using various cutting tools.

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