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Burr formation during dry milling of wrought aluminum alloys

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Abstract

In this article, a multi-level experimental study on dry milling of 2024-T351 and 6061-T6 aluminum alloys is used to prescribe an operational window to control and minimize burr height (B_h) in milling. Maximum height of exit burr and exit up milling side burr were measured. Statistical tools were then used to define the dominant process parameters on B_h. The effects of feed rate, depth of cut, friction, tool coating, insert nose radius (Rε) and material properties on milling burrs profiles are discussed. The experimental results show that machining with larger Rε leads to bigger exit bottom burr and smaller exit up milling side burr. In addition, coated tools significantly affect B_h in slot milling operations.

Keywords: Dry milling, burr height, cutting parameters, cutting tool, aluminum alloys

Introduction

A phenomenon similar to the formation of chips is formation of burrs at the end of a cut. Most of all numerous traditional and non-traditional manufacturing processes (e.g. Machining process) generate burr. Burr removal is expensive, time consuming and is considered as non-productive operation. As pointed out by Gillespie [1],deburring and edge finishing on precision components may constitute as much as 30 percent of the cost of the finished parts. In addition, the secondary finishing operation is difficult to automate, thus may become a bottleneck in a production line [2]. Burr formation problem has been addressed by researchers from various aspects. Several geometric factors, such as tool exit/entrance, in-plane exit angle, undeformed chip geometry and EOS, dominated burr formation for a specific material with certain ductility [3-4]. The main dominant factors on burr formation are mainly material properties, workpiece geometry, cutting conditions, tool parameters and machining strategy [5]. In addition, cutting edge geometry has a strong influence on the burr formation process. Sharp cutting edge tool with positive rake angle in the case of milling operation, avoids built-up edge formation thus decreasing B_h [5]. To identify the large and small burrs that form on the component edge, the terms “primary burr” and “secondary burr” were introduced. Secondary burrs are smaller than depth of cut, while primary burrs are larger. Chern [6] analysed burr formation in face milling of aluminum alloy, and found that secondary burr formation is dominated by depth of cut and feed rate respectively. As per author's knowledge, regardless of previous experimental studies on face milling burr formation [7-8], very low volume of information is available about dominant process parameters on slot milling burrs size. Exit up milling side and exit bottom burrs (see Fig.1) are the largest burrs in slot milling [9].

(a) (b)

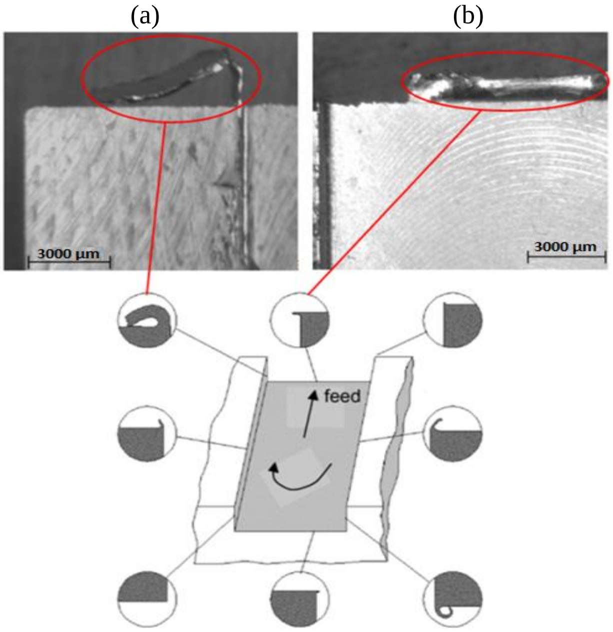


Figure 1: Slot milling burrs ; (a) Exit up milling side burr, (b) Exit bottom burr (*adapted* from [10])

In the present research study, statistical tools and experiments were used to characterize burr formation in slot milling of 2024-T351 and 6061-T6 aluminum alloys. The goal is simultaneous determination of the individual and interactive effects of process parameters that affect on mechanism and dimension of studied burrs during slot milling operation (see Fig.2). A multi-level full factorial design of experiment (see Table.1) is used to design an efficient way to prevent and/or minimize the B_h in machining process. The experimental procedure is presented in second section, followed by results and discussion in third section. This study is concluded in section four.

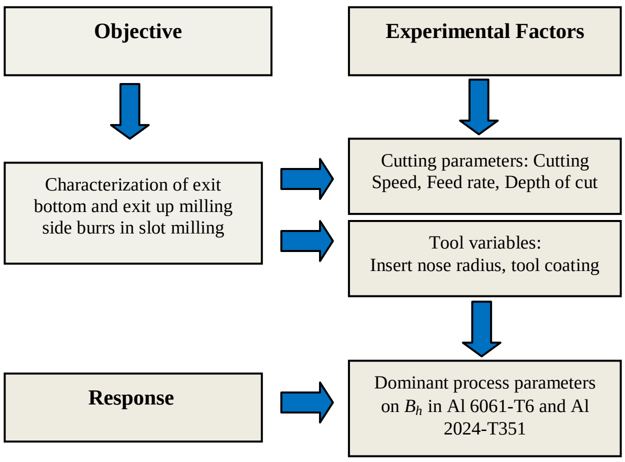


Figure 2: Theme of the experimental characterization and control of burr formation in slot milling

Experimental procedure

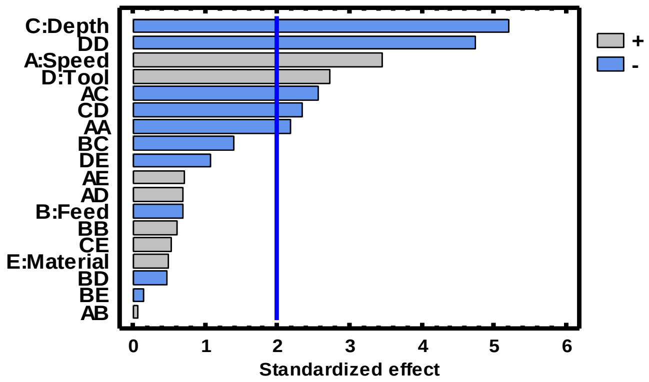
Slot milling tests are carried out on specimens with dimensions of 38 mm length, 38 mm width and 12 mm thickness, under orthogonal cutting condition. A multi-level factorial design ($3^3 \times 2^2$) was selected. The experimental factors and their levels are shown in Table 1. Cutting tool and workpiece materials were treated as qualitative factors while other remaining factors were considered as quantitative. In total, 108 experiments were necessary to complete the study. The tests were not repeated. An optical microscope with 70X magnification, equipped with high resolution camera was used for recording the burrs images. The burr size measurements were conducted on recorded images. Maximum B_h is adopted as scale of burr height in this study.

Table 1: Cutting parameters and their levels

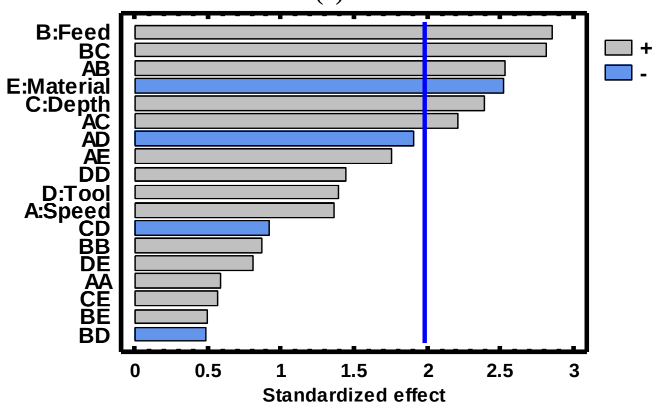
Experimental parameters		Level		
		1	2	3
A: Cutting speed		300	750	1200
B:Feed per tooth		0.01	0.055	0.1
C: Depth of cut		1	-	2
D: Tool	*Insert Ref*	IC 328	IC 908	IC 4050
	Coating	TiCN	TiAlN	TiCN+ Al_2O_3+TiN
	Rε (mm)	0.5	0.83	0.5
E: Material		Al 2024-T351	-	Al 6061-T6
Cutting fluid		None		

Results and discussion

The results presented in this article do not consider the possible effects caused by the tool, material quality and vibration of the system. Each burr type behaves differently based on applied cutting conditions. Therefore, burrs control at various edges of machined parts becomes more complicated. Figure 3 presents a standardized Pareto chart for the responses obtained in each material. A Pareto chart compares the relative importance and statistical significance of the main and interaction effects between parameters. The reference line in the Pareto chart shows that the effects are statistically significant at a 95% confidence interval. This chart identifies influential factors in order of decreasing contribution. Reading the Pareto charts, the predominant role played by each cutting process parameter and their interactions can be understood.



(a)



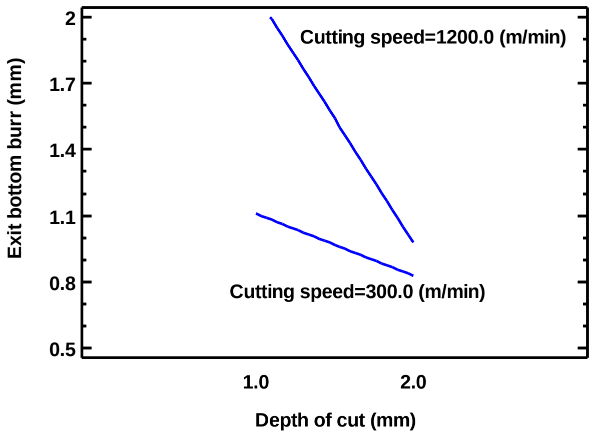
(b)

Figure 3: Pareto chart (a) exit bottom burr; (b) exit up milling side burr

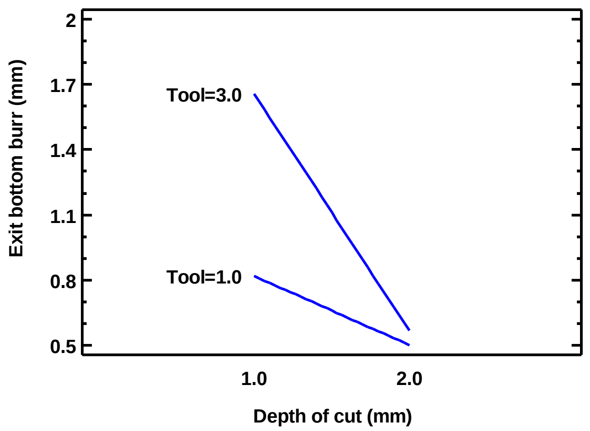
According to Figure 3(a), exit bottom burr is influenced by direct effects of depth of cut (C), cutting speed (A) and cutting tool (D) and interactive effects of insert nose radiuses and coatings in tool (DD. As can be seen in Figure 3(b), Exit up milling side burr is dominated by feed rate (B), interaction effects between feed rate-depth of cut (BC) and cutting speed- feed rate (AB), followed by material properties (E) and depth of cut (C). The effect of material properties on exit up milling side burr formation is evident from Pareto chart in Figure 3(b). The main mechanical properties with significant effect on burr formation are normal yield strength and tensile strength [11]. The effect of tool on exit bottom burr size, caused by inserts nose geometry and coating is also significant.

Interactive effect analysis

It is believed that the interactive effects between process parameters have a significant effect on burr formation profile. The interactive effect diagrams of the exit bottom burrs and exit up milling side burrs are presented in Figure 4. According to Figure 4(a), the B_h is significantly decreased with increase in depth of cut and cutting speed. The B_h is sensitive to variation in tool. Based on Figure 4(b), exit bottom burr is not highly influenced under changes in cutting speed, when the fixed depth of cut 2mm is used. However when depth of cut is fixed at 1mm, higher speed generates larger exit bottom burrs. As clearly shown in Figure 5(a), the exit up milling side burr height is not influenced under various levels of feed per tooth at lower cutting speed (i.e.300m/min). The same trend is observed when low feed per tooth (i.e. 0.01 mm/z) is employed with various levels of depth of cut as depicted in Figure 5(b). In addition, increase in feed rate, while using fixed depth of cut (i.e.2mm) yields into a continuous increase in B_h.

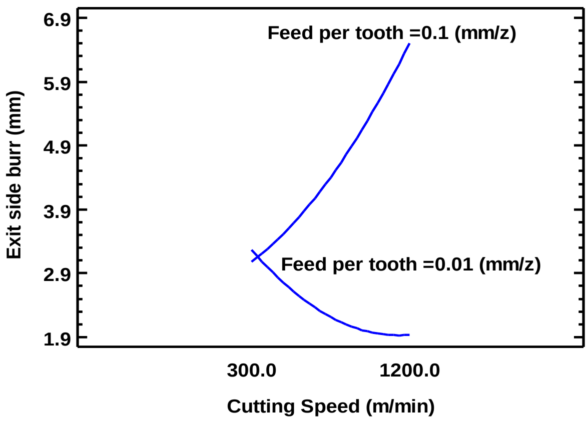


(a)

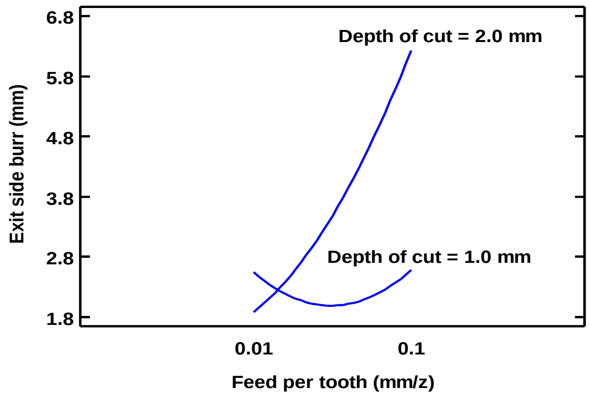


(b)

Figure 4: (a) Interactive effect of cutting speed (A) and depth of cut (C); and (b) interactive effect of depth of cut (C) and tool (D) on exit bottom burr height



(a)

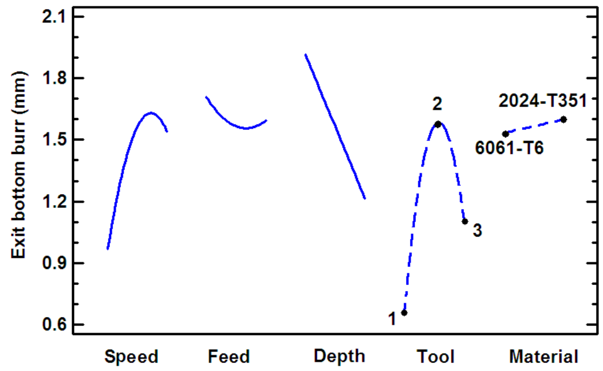


(b)

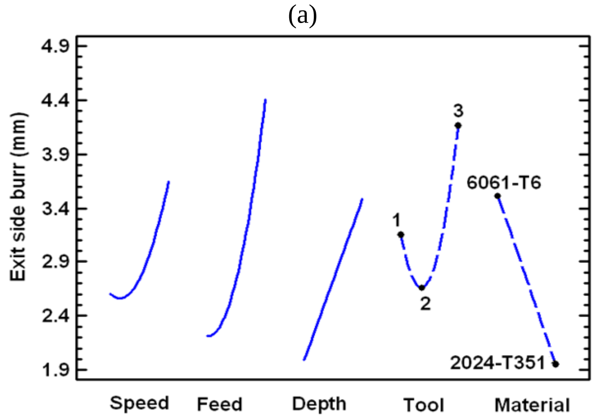
Figure 5: (a) Interactive effect of cutting speed (A) and feed per tooth (B); and (b) interactive effect of depth of cut (C) and feed per tooth (B) on exit up milling side burr height

Main effect plot

The plot of the direct effects in Figure 6 highlights the most important factors on both investigated burrs. In metal cutting, feed rate, depth of cut and cutting speed are the main controlling parameters [12]. According to Figure 6, an increase in feed per tooth and depth of cut, leads into an increase in exit up milling side burr and a decrease in exit bottom burr. This is mainly due to mechanism of slot milling burr formation while exit bottom burr is formed by a loss of material from the exit up milling side burr. In addition, burrs dimension are highly affected by tool geometry.



(a)



(b)

Figure 6: Direct effect plot for (a) Exit bottom burr, (b) Exit up milling side burr

Materials with higher machinability generate more friction between the chip and tool. The effect of friction can be divided into three basic mechanisms, one due to asperity deformation, one due to adhesion and one due to particle ploughing. The friction angle (λ) applied on exit up milling side of machined parts can be calculated as:

$$\tan(\lambda - \alpha_r) = F_t \times F_r^{-1} \quad (1)$$

Where λ = friction angle; α_r = rake angle; F_t = cutting force; F_r = radial force;

According to Eq.(1), when the tool faces friction decreases, there is a corresponding increase in the shear angle (φ) and accompanying decreases in the chip thickness. Thus the plastic strain associated with chip formation is reduced. This will result into an increase in exit bottom burr size and a decrease in exit up milling side burr size.

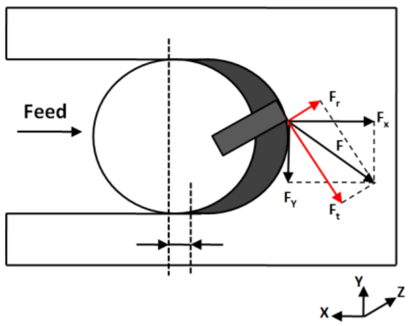


Figure 7: Slot milling under orthogonal cutting conditions

According to Figure 6(a), the effect of tool on exit bottom burr size is significant. In addition, it can be observed that machining tests with tool 2 with larger insert nose radius (0.83mm) has resulted into larger exit bottom burr as compared with those conducted using tools 1 and 3 with smaller insert nose radius (0.5mm).

Conclusion

The burr size for exit up milling side burr and exit bottom burr in slot milling of aluminum alloys 6061-T6 and 2024-T351 were investigated using a multi-level factorial design of experiment. According to experimental results and statistical analysis, the following conclusions were drawn:

- The exit burrs are controlled by different factors: the exit up milling side burr is controlled by the feed rate and the mechanical properties of the materials being cut while the exit bottom burr (rollover burr) is controlled by the depth of cut, cutting speed and tool geometry.
- The effect of various coated cutting tools with various insert nose radiuses on exit burrs height was studied. It was found that, regardless the significant effect of high speed machining on burr formation profile, using depth of cut closer to the insert nose radius, leads to primary exit bottom burr. Bigger insert nose radius leads to smaller size in exit up milling side burrs, while generation of secondary exit bottom burrs is expected following using cutting tools with insert nose radius smaller than the depth of cut.
- Interactive effects between speed and depth of cut (AC) and depth of cut and tool (CD) dominated on exit bottom burr, while exit up milling side burr is influenced by interactive effect of depth of cut and feed per tooth (BC) and cutting speed and feed per tooth (AB). The conducted milling tests on Al 2024-T351 has shown smaller size in exit up milling side burrs as compared with Al 6061-T6

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