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Procedia CIRP 17 (2014) 755 – 759
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Variety Management in Manufacturing. Proceedings of the 47th CIRP Conference on Manufacturing Systems

Analysis of friction and burr formation in slot milling

Seyed Ali Niknam*, Victor Songmene

Department of Mechanical Engineering, École de technologie supérieure (ÉTS)
1100, Notre-Dame West street, Montreal, QC, H3C-1K3, Canada

* Corresponding author. Tel: +1-514-396-8869 ; fax: +1-514-396-8530. *E-mail address:* seyed-ali.niknam.1@ens.etsmtl.ca

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Abstract

Burr formation is one of the most common and undesirable phenomenon occurring in machining operations that reduces assembly and machined part quality, and it should be avoided or at least reduced. To remove burrs, a non-value added secondary operation known as deburring is required for post-processing and edge finishing operations. Among conventional machining operations, milling burr formation is a very complex mechanism. Therefore, research and close attention are still needed in order to minimize and control milling burr formation. This could be achieved by effective burr prevention through adequate understanding of the basic mechanisms of burr formation and an accurate proposal of optimum cutting parameters. In recent reported works in literature, exit up milling side burr was characterized as the longest and thickest milling burr which is formed by loss of material during exit burr formation. Since burr thickness is a critical parameter for better selection of the deburring time and method, a good knowledge on the effects of cutting parameters, friction and tool geometry and coating on this burr is important for better selection of deburring methods. Although friction angle has a direct proportion to negative shear angle, radial and tangential cutting forces, but very limited information is still available on correlative studies between burr size and friction angle in milling operation. This paper presents the effects of cutting parameters on friction angle and the correlation between friction angle and exit up milling side burr thickness during slot milling of aluminum alloys. To that end, a computational algorithm that was recently proposed by authors is used to calculate the friction angle λ for each material when using specific levels of cutting speed, feed per tooth and undeformed chip thickness. Experimental results show that lower friction angle is resulted when using larger chip load. Consequently, larger friction angle is obtained when exit up milling side burr thickness decreases and exit bottom burr thickness increases.

Keywords: Slot milling; Burr; Aluminum alloy; Friction

Nomenclature

B_t	Burr thickness
ap	Axial depth of cut
vc	Cutting speed
f_z	Feed per tooth
Z	Number of teeth
θ	Tool rotation angle
θ_p	Cutter pitch angle
φ_j	Immersion angle for flute j
$h(\varphi)$	Chip thickness (mm)
μ	Friction coefficient
λ	Friction angle
ϕ	Shear angle
σ_e	Yield strength
$R\varepsilon$	Insert nose radius
F_r	Radial cutting force
F_t	Tangential cutting force

1. Introduction

Burr formation, a phenomenon similar to chip generation, is a common problem that occurs in several industrial sectors, such as the aerospace and automobile sectors. It has also been among the most troublesome impediments to high productivity and automation, and largely affects the machined

doi:10.1016/j.procir.2014.02.032

part quality. To ensure competitiveness, precise and burr-free components with tight tolerances and better surface finish are demanded. Among machining burrs, milling burr formation involves a more complex mechanism (multiple burrs formed at different locations and with varying shapes and sizes-see Fig.1). This leads to numerous difficulties during deburring processes, and therefore, it is extremely beneficial to limit and control milling burrs rather than deburring them in subsequent finishing operations. This can be achieved by burr size minimization or effective burr prevention through adequate understanding of the basic mechanisms of burr formation and an accurate proposal of optimum cutting parameters. Comprehensive knowledge of factors governing burr formation is thus essential in order to reduce the incidence of burr formation.

The effects of numerous process parameters on milling burrs were reported using experimental studies [1-10] and analytical modeling approaches [11-16]. According to [17-19], most of reported works in literature characterize the burr height B_h, but from deburring perspective, the burr thickness B_t is of interest, because it describes the time and method necessary for deburring operation [17]. Regardless of extensive research works on understating, modeling and characterization of milling burrs, few works [19-21] present the correlation between burr size and friction angle λ and friction coefficient μ.

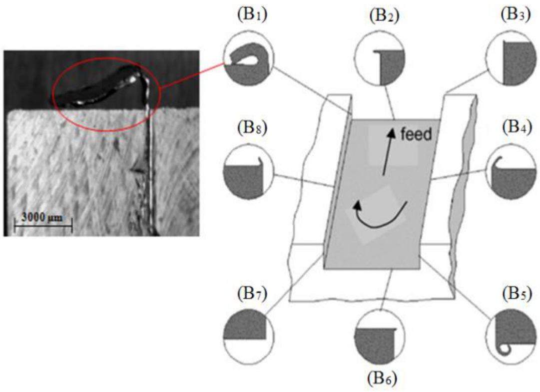

Fig.1. Overview of slot milling burrs

In metal cutting, feed per tooth f_z, depth of cut ap, and tool geometry are the main controlling parameters [5] that highly affect the directional cutting forces. As shown in Fig.2, when using a constant value of depth of cut ap, irrespective to level cutting speed vc and material used, the resultant cutting forces increase when feed per tooth f_z is increased. In recent studies by Niknam and Songmene [16,22, 23], exit up milling side burr (B_t) was found as the longest and thickest slot milling burr (Fig.1) that can be highly controlled by variation of feed per tooth f_z and depth of cut ap. The thickness of this burr was analytically modeled by Niknam and Songmene [24] using certain levels of assumptions and relatively similar method as implemented in [11]. The only model's unknown parameter in [24] is tangential cutting force F_t that itself is directly affected by cutting parameters, such as feed per tooth f_z and depth of cut ap. Other input parameters include a constant value as a function of negative shear angle, depth of cut ap and yield strength σ_e. This model was later completed in [25] by proposing a computational model that can approximate the tangential and radial cutting forces (F_r,F_t) and consequently simulate the size (thickness) of exit up milling side burr (B_1), which is quoted as "B_t" in this article. In order to calculate the chip thickness, tangential and radial cutting forces (F_r,F_t), friction angle λ, friction coefficient μ and B_t during slot milling of aluminum alloys (AAs), a similar method as that presented in [24,25] will be used in this work and correlation between B_t and friction angle λ at exit side of slot milled parts will be investigated.

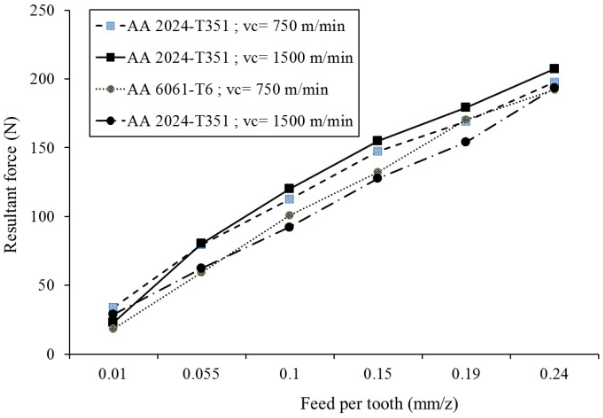

Fig.2. Resultant cutting force during slot milling of AAs 2024-T351and 6061-T6, when depth of cut ap is 2 mm

2. Experimental plan

The following experimental devices and procedure were used in this work:

- **Materials:** AAs 6061-T6 and 2024-T351 (Table 1).
- The cutting operations were performed on a 3-axis CNC machine tool (Power: 50kW, Speed: 28000 rpm; Torque: 50 Nm).
- Six levels of feed per tooth f_z [0.01-0.24] and two levels of cutting speed vc [750; 1500] were used under dry condition at constant level of depth of cut ap =1mm. An Iscar end milling tool (E90-A-D.75-W.75-M) with three teeth Z=3 and diameter D=19.05mm was used.

Table 1. Mechanical properties of studied AAs [24]

Material	Mechanical Properties		
	Brinell Hardness	Yield Strength	Elongation at Break
AA 6061- T6	95 HB	275 MPa	17 (%)
AA 2024- T351	120 HB	325 Mpa	20 (%)

3. Results

In order to perform more comfort deburring operation, burr size minimization can be conducted by facilitating the transition of primary burrs to secondary burrs. This phenomenon is highly affected by friction and it may occur when burr leans towards the transition material and breaks off from the machined surface. The main reasons of friction in cutting operations are asperity deformation, adhesion and particle ploughing [19]. Using the proposed methods in [24,25], the tangential and radial cutting forces (F_r, F_t) were theoretically calculated. According to [26], friction coefficient μ in orthogonal milling can be approximated as:

$$\mu = \tan(\varphi) = F_r \, . \, F_t^{-1} \qquad (1)$$

Friction angle λ is obtained using Eq.(2) as follows:

$$\lambda = \arctan(\mu) \qquad (2)$$

Referring to Eqs.(1-2), the theoretical friction angle λ for each material when using certain levels of cutting speed *vc*, feed per tooth f_z and undeformed chip thickness h_m is calculated (Figs.3-4). Knowing that the undeformed chip thickness h_m is a function of feed per tooth f_z, it could be inferred that the friction angle λ at tool faces decreases when increasing the feed per tooth f_z and consequently undeformed chip thickness h_m. This ultimately leads to secondary burr formation along up/down milling sides (B_t and B_3) that requires less efforts, precision and time for deburring than that required for exit bottom side burr (B_2). As shown in (Figs.3-4), larger friction angle λ *is observed in* AA 2024- T351 that is harder than AA 6061-T6 (Table 1).

When friction at tool faces decreases (Eq.1), there is an increase in the shear angle ϕ and accompanying decrease in the chip thickness $h(\varphi)$. Therefore, the plastic strain associated with chip formation is reduced. This results to longer and thicker exit up milling side burr [19]. In this condition, side burrs formed instead of exit bottom (B_2) or entrance bottom (B_6) burrs (Fig.1). According to face milling burr formation mechanism, exit bottom burr (B_2) is formed by loss of material from exit up milling side burr [27]. Assuming similar burr formation mechanism in exit side of face milling and slot milling operations, transition from primary to secondary burr formation is observed on the exit burrs along up/down milling sides (B_t and B_3).

When Transition from primary to secondary burr formation is not correctly done, primary exit bottom burr (B_2) appear in the exit side when tool leaves the machined part (Fig.5(a)). When burr leans smoothly towards the transition material and breaks off from the machined surface, due to smaller friction angle λ at tool faces, longer and thicker B_t and shorter and thinner B_2 are resulted (Fig.5(b)). This exhibits that, since exit down milling side burr (B_3) has usually a negligible size, then cutting trials to reduce the B_2 size led to longer and thicker B_t [19]. According to [19], higher levels of cutting speed *vc* and insert nose radius Rε increase F_r to a large extend, particularly where depth of cut *ap* is smaller than the insert nose radius Rε. In addition, materials with higher machinability generate larger F_r and eventually less friction occurred between chip and tool [26]. Furthermore, presence of slight plastic deformation, serious rubbing and ploughing effects yield to heat generation and longer and thicker primary exit bottom burr (B_2). This phenomenon tends to intensify during high speed milling operations.

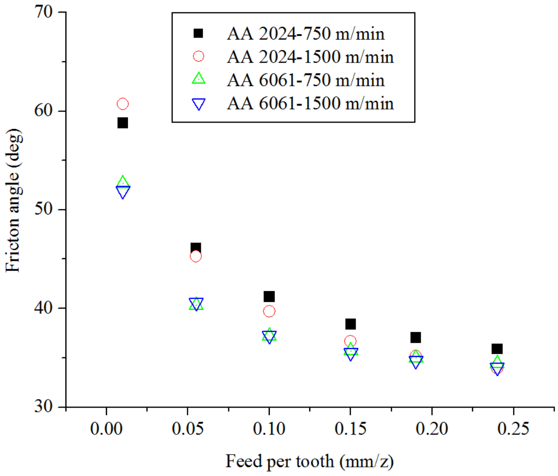

Fig.3. Friction angle λ vs. feed per tooth f_z

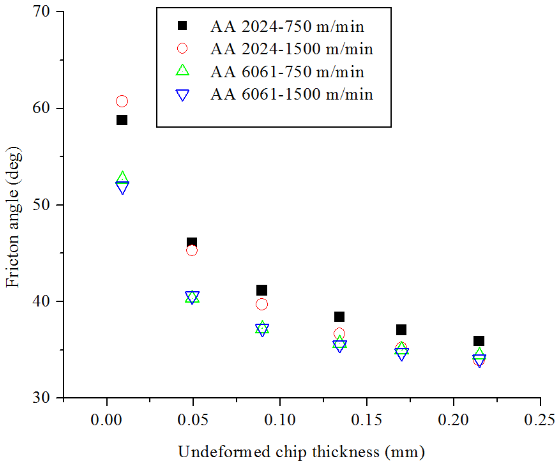

Fig. 4. Friction angle λ vs. undeformed chip thickness h_m

Irrespective to levels of cutting speed *vc* and feed per tooth f_z used, the lower friction angle λ was obtained for AA 6061-T6. This confirms that friction angle λ decreases during machining of harder materials, especially at lower levels of feed per tooth f_z that cutting tool pushes the work part to the side rather than cutting it. This eventually leads to large primary exit bottom burr (B_2) formation. As shown in Fig.6, when using higher levels of feed per tooth f_z, relatively similar friction angle λ can be obtained for both materials. This not only increases production rate, but it also facilates the cutting operations and decreases tool faces frictions, therefore secondary exit bottom burr (B_2) formation is anticipated.

As shown in Fig.5, irrespective to material and cutting speed used, B_t increases with decreased friction angle λ at tool face. This also reconfirms that the B_t largely varies along variation of feed per tooth f_z. This phenomenon verifies the conclusion made in [19,26], stating that exit bottom burr (B_2) is formed by loss of material from the exit up milling side burr (B_t).

Figure 5(a)

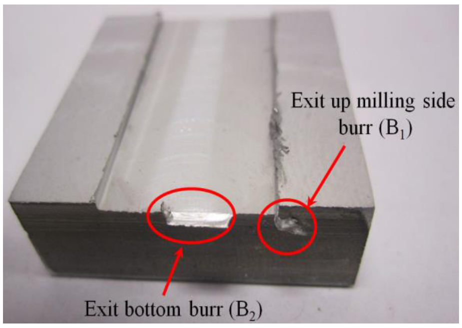

Figure 5(b)

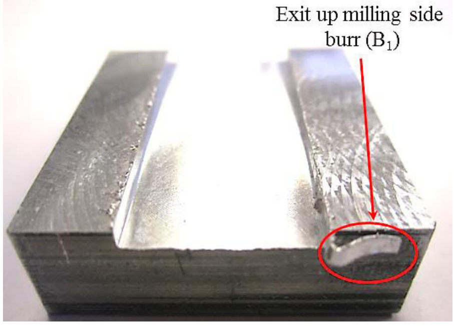

Fig. 5. Slot milling exit burrs

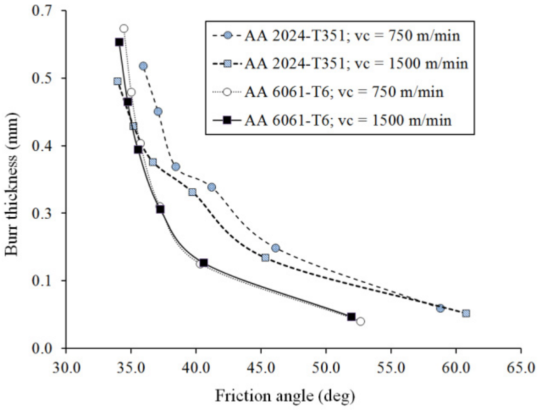

Fig. 6. Friction angle λ vs. burr thickness B_t

4. Conclusion

In this work, a similar computational algorithm as that previously presented by authors was implemented and chip thickness, radial and tangential cutting forces (F_r,F_t), friction angle λ and B_t were calculated during slot milling of aluminum alloys (AAs). This was followed by studying the correlation between B_t and friction angle λ at exit side of slot milled parts.

It was found that, when friction at tool faces increases, then the shear angle ϕ and plastic strain associated with chip formation are reduced. This results to longer and thicker exit bottom burr B_2 and shorter and thinner exit up milling side burr (B_t) [27]. In this case, transition from primary to secondary burr formation is not correctly done, and consequently primary exit bottom burr (B_2) appear in the exit side when tool leaves the machined part.

The effects of feed per tooth f_z, material hardness and cutting speed vc on friction angle λ were investigated. Smaller burr thickness B_t is resulted with increased friction angle λ. Consequently, smaller primary exit bottom burr size is resulted, which in fact reduces the necessity of secondary deburring operations.

Acknowledgements

This work was partially supported by consortium for research and innovation in aerospace in Quebec (CRIAQ), and Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) by the intermediary of the Aluminum Research Centre – REGAL

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