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ON THE FACE MILLING BURR FORMATION MECHANISMS AND MINIMIZATION STRATEGIES AT HIGH TOOL ENGAGEMENT

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ABSTRACT

It has been recognized that on ductile materials, high radial tool engagement conditions produce the largest burrs in face milling operations. Ideally, high radial engagement is avoided by configuring the tool path such that the mill is kept within the feasible offset region—a region that satisfies user requirements—of a given workpiece geometry and material. Fulfillment of this condition, however, is often difficult due to geometrical complexity of the manufactured components and cycle time constraints. For this reason there is great motivation to minimize burr formation at high tool engagement. In this paper, the mechanisms of burr formation and the effect of cutting parameters under high radial engagement are investigated, and possible burr minimization strategies are discussed. To this end, face milling tests results conducted by CODEF members and other researchers on different materials were examined. The proposed minimization strategies focus on the optimization of the following parameters: depth of cut, insert nose sharpness, lead angle, and

axial rake angle, to promote a transition from primary to secondary burr formation.

INTRODUCTION

Machining burrs have been defined as undesired projections of material beyond the theoretical edge of a workpiece, due to plastic deformation incurred by the cutting process. In face milling operations, the largest burrs are formed when radial tool engagement is beyond a critical value. The height of these burrs approach, and may even exceed, the depth of cut. Tool path planning can be used to minimize burr formation by machining the workpiece at low radial engagement conditions. In more practical terms, tool paths are drawn within the limits of a feasible offset region as determined by production tolerances and empirical burr size data from a given material. This approach, however, becomes too restrictive when the geometry of the workpiece reaches a certain level of complexity, owing to the following reasons:

- Intricate geometries require long and intricate tool paths that may exceed cycle time constraints.
- The intricacies of the paths may require small tools for maneuverability, but small tools slow down production rates.

In the automotive industry, for example, feature size of a considerable number of components, such as engine cylinder blocks and heads, transmission valve bodies, etc., is quite small compared to the size of the mills used. This often renders a feasible offset region that is too restrictive to apply and thusly high tool engagement conditions are inevitable. A thorough understanding of the mechanism of burr formation under high tool engagement is cardinal to the improvement of edge quality in a wide scope of applications. In this context, implementation of effective burr minimization strategies can broaden the feasible offset region and satisfy edge quality tolerances using simpler, shorter tool paths, and large tools relative to feature size, for increased productivity.

In this study, following a review of basic concepts on burr formation in face milling, formation mechanisms at high tool engagement conditions are discussed. Experimental data showing the peculiarities of burr formation under these circumstances is shown. Lastly, it is proposed that, under these circumstances, minimization strategies should focus on the optimization of the following parameters: depth of cut, insert nose sharpness, lead angle, and axial rake angle, to promote a transition from primary to secondary burr formation.

LIMITATIONS OF TOOL PATH PLANNING FOR BURR MINIMIZATION

The concepts of tool entrance/exit and tool engagement have been used in the computation of tool paths that minimize burr formation in planar milling (Narayanaswami and Dornfeld, 1997). In essence, contour-parallel paths that minimize exit regions and maintain in-plane exit angles below a critical value, as indicated by experimental evidence, are drawn. This approach is efficient with simple workpiece geometries, whose feature sizes aren't small compared to the diameter of the cutter. For more

complex geometries, however, this approach would require intricate tool paths and multiple passes that may be too long to satisfy cycle time constraints. Pockets that are small compared to the diameter of the mill are the most common problem areas.

Figure 1 illustrates the compromise relationship between path length and burr reduction by contour-parallel path planning. Figure 1(a) depicts a single pass milling operation. Path length is shortest but burr-prone, because tool exit and high radial engagement conditions exist. Figure 1(b) represents the opposite scenario, a contour-parallel tool path with tool entrance and low engagement throughout. Burrs are minimized, but cycle time may result too long. In an attempt to make tool paths less restrictive, and after the recognition that tool entrance condition does not guarantee small burrs, tool exit/entrance and width of cut considerations have been used to define a feasible offset region for path planning (Ramachandran, 2003). Feasible offset region is defined as a bounding frame wherein tool paths that satisfy edge quality specifications can be drawn. Within the feasible offset region, the shortest possible tool path is computed. Exit Order Sequence Theory (EOS) is also considered to minimize burrs in tool exit regions by adjusting tool geometry. The presence of pockets that are considerably smaller than the mill's diameter, however, may still render paths that are too long, and impractical, due to limited tool maneuverability. Due to this limitation, feasible offset region is not applied in pocket edges and deburring techniques are relied upon.

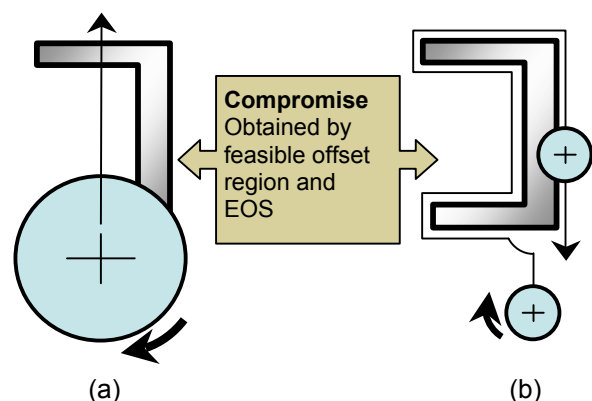


FIGURE 1. TOOL PATH SCENARIOS IN FACE MILLING. (a) SINGLE PASS MILLING OPERATION, (b) CONTOUR-PARALLEL MILLING.

IN-PLANE EXIT/ENTRANCE ANGLE AND RADIAL TOOL ENGAGEMENT

Definition

In-plane exit/entrance angle Ψ is defined as the angle between the cutting velocity vector V , at the point where the tool coincides with the edge of the workpiece, and the vector that contains the theoretical edge, pointing from tool entrance to tool exit region, $EnEx$ (Figure 2). V is composed by the tangential velocity V_t and

feedrate f :

$$V = V_t + f \quad (1)$$

$$V_t = \omega \times r \quad (2)$$

where ω is the angular speed and r the effective radius of the mill. In face milling process, V can be approximated to the tangential velocity V_t , as the feed component f is usually very small compared to V_t . Under this condition, tool exit occurs when $0^\circ < \Psi \leq 180^\circ$, whereas tool entrance corresponds to the range $180^\circ < \Psi \leq 360^\circ$.

As shown in Figure 2, in-plane exit/entrance angle is a measure of the degree of radial tool engagement, or width of cut. Although less general, tool engagement is also often expressed in terms of an offset distance e between the spindle axis and the edge of the workpiece. The following expression relates Ψ and e :

$$\Psi = 90^\circ + \sin^{-1}(e/r) \quad (3)$$

In the case of tool exit condition, if the tool is inside the workpiece and its periphery tangent to the edge, engagement is maximum, and in-plane exit angle is 180° . Analogously, when the tool is outside the workpiece and tangent to the edge, engagement is minimum, and Ψ equals 0° . High radial tool engagement condition is considered to occur in the interval $90^\circ < \Psi < 270^\circ$.

Effect on Burr Size

Several studies on milling burr formation have determined that in-plane exit angle has a strong effect on burr size. Schäfer (1978) found that an increase in exit angle results in increasing burr height, whereas a decrease in exit angle to less than 30° leads to negligible burr size. Kishimoto et al. (1981) first recognized that primary to secondary burr transition is highly sensitive to exit angle and depth of cut. Their edge-parallel tests on medium carbon steels lead to the conclusion that exit burr height increases with increasing in-plane exit angle, up

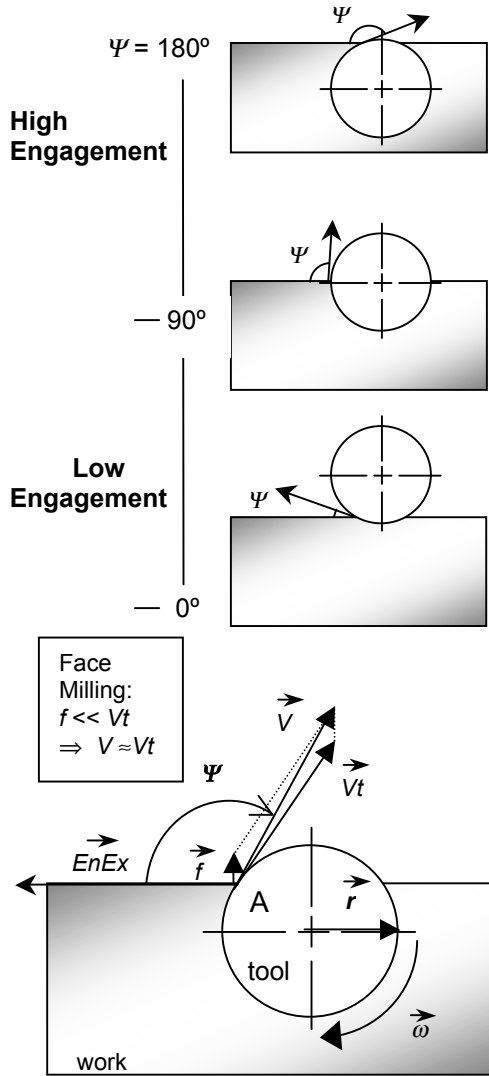


FIGURE 2. SCHEMATIC REPRESENTATION OF IN-PLANE EXIT ANGLE Ψ AND RADIAL TOOL ENGAGEMENT. $EnEx$: WORKPIECE EDGE VECTOR, POINTING FROM TOOL ENTRANCE TO TOOL EXIT REGION, V : CUTTING SPEED VECTOR, ω : ANGULAR SPEED OF THE TOOL.

to a critical value at which a sudden transition from primary to secondary burr formation occurs. This critical value increases with increasing depth of cut. Chern (1993) observed the same behavior on 1100 aluminum alloy, and remarked that burr morphology changes with in-plane exit angle. This result indicates that changes in formation mechanism of machining burrs take place when radial tool engagement is varied.

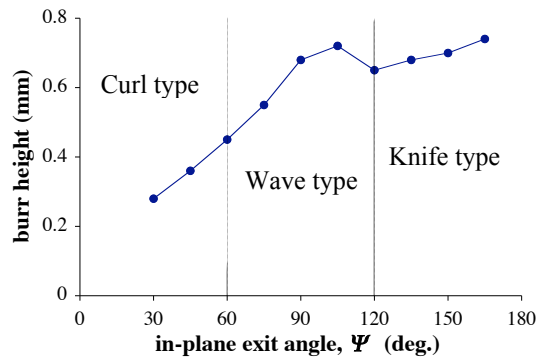


FIGURE 3. VARIATION OF BURR HEIGHT AND BURR TYPE VS. IN-PLANE EXIT ANGLE. MATERIAL: Al 1100, D.O.C. = 0.76 mm, FEED/TOOTH = 0.03 mm, CARBIDE CUTTER. AFTER CHERN, 1993.

CHARACTERISTICS OF BURR FORMATION AT HIGH RADIAL TOOL ENGAGEMENT

High tool engagement condition has been observed to produce the largest milling burrs. Burr formation mechanisms at high engagement are different from those at low engagement; this is caused by a change in plastic zone size in the transition material ahead of the tool. Owing to dissimilar formation mechanisms, it has been observed that the effects of tool entrance or exit condition, cutting conditions, and tool geometry, are not the same under high and low engagement conditions.

Effect of Tool Exit and Tool Entrance Conditions

Figure 4 shows schematically tool exit and tool entrance regions in a sample workpiece. In both milling and orthogonal cutting, tool exit creates forward flow of material. On the other hand, tool entrance always induces backward flow during

orthogonal cutting, but it might also promote forward flow during milling. Forward flow creates larger burrs than backward flow due to the absence of back-up material. In face milling of ductile materials, entrance burrs are not necessarily smaller than exit burrs. High radial engagement induces forward flow of transition material in tool entrance regions. A typical example of this phenomenon in AlSi alloy is shown in Figure 5 (Avila, 2003). In this case, entrance burrs are as large as exit burrs and possess the same morphology (knife-type); their height is approximately equal to the depth of cut.

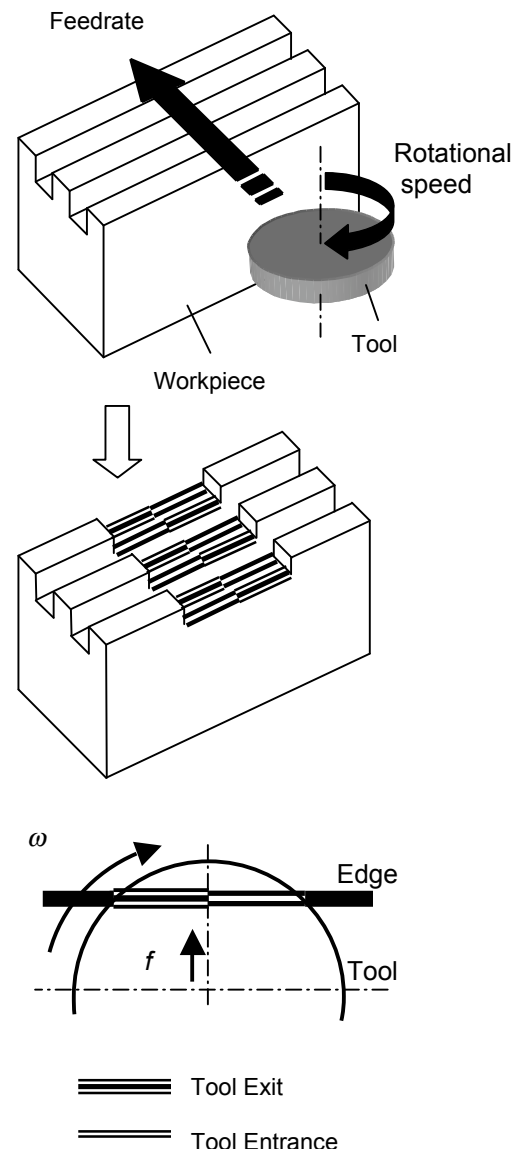


FIGURE 4. SCHEMATIC OF TOOL EXIT AND TOOL ENTRANCE REGIONS.

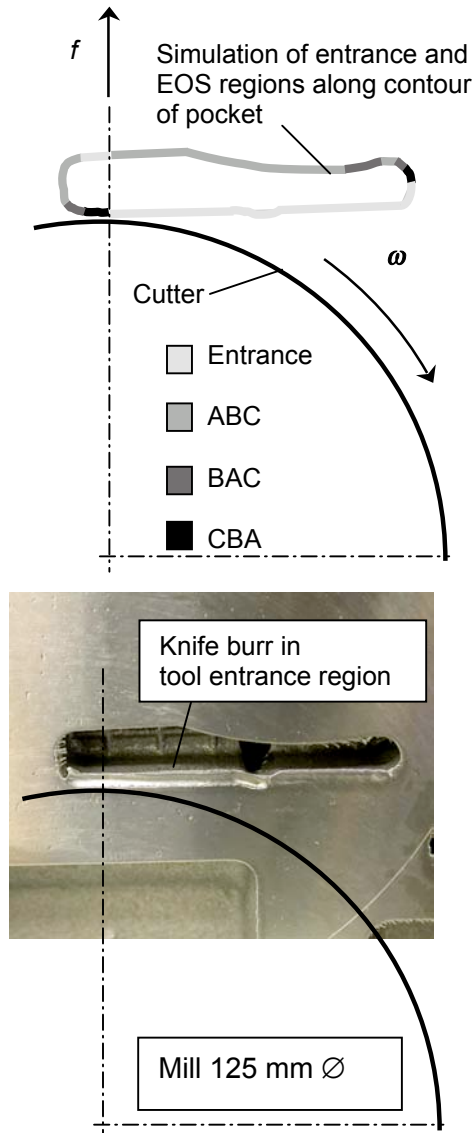


FIGURE 5. PHOTOGRAPH OF KNIFE TYPE BURR DEVELOPED IN A POCKET AND SIMULATION OF TOOL ENTRANCE AND EOS REGIONS. A KNIFE-TYPE BURR DEVELOPED ALONG THE ENTIRE TOOL ENTRANCE REGION OF THE POCKET. MATERIAL: AISi7Mg, $V_c = 2500$ m/min, $f_z = 0.12$ mm/tooth, DEPTH OF CUT = 1.2 mm (AVILA, 2003).

Evidence that at high radial engagement conditions, burr height is approximately uniform regardless of tool entrance or exit condition, has an important implication: it shows that the burr formation and chip formation processes are independent. As discussed later, the mechanism of formation of the cumulative rollover burr explains this phenomenon.

Effect of Exit Order Sequence (EOS)

While burr formation in face milling is a high-degree of freedom phenomenon that depends on work material properties, tool/workpiece geometry, cutting speed, etc., geometry considerations can provide an indication of the burr formation mechanism and thus their size. Hashimura (1993) proposed that the orientation of the minor and mayor cutting edges at tool exit position affect burr formation mechanism. In further work by Hashimura, Hassamontr and Dornfeld, (1995, 1999 a), Exit Order Sequence Theory (EOS) was proposed as a milling burr size prediction algorithm. EOS computes the exit order of 3 characteristic points of the cutter from the following geometric parameters: axial rake, radial rake, and lead angles of the cutter, uncut chip thickness (w , derived from feed per tooth), depth of cut (d), and in-plane exit angle (Ψ). The algorithm ranks burr sizes according to six possible exit order sequences. The EOS chip flow model is shown in Figure 7. Three key assumptions are made: (1) tool and material deformation are negligible and cutting takes place, (2) tool corner radius is small, and (3) feed can neglected since $f \ll V_c$.

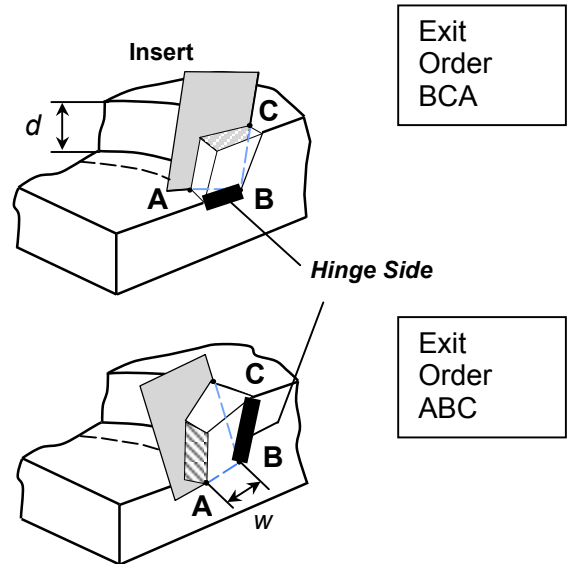


FIGURE 6. EXIT ORDER SEQUENCE THEORY (EOS) CHIP FLOW MODEL. B DENOTES THE TOOL TIP; A AND C ARE DEFINED ACCORDING TO CUTTING WIDTH (w) AND DEPTH OF CUT (d), RESPECTIVELY. HINGING AT THE TRANSITION SURFACE MINIMIZES BURR FORMATION AT THE MACHINED SURFACE (EXIT ORDER ABC).

Experimental studies have shown that EOS prediction shows good correlation with burr size measurements at low radial engagements, $\Psi < 90^\circ$ (for example: Hashimura et al., 1995, 1999 a). Contrariwise, empirical results at high radial engagement conditions do not show consistent correlation with EOS theory (e.g. Lee and Bansal, 2001; Avila, 2003). This is explained by the changes in burr formation mechanisms and transition from primary to secondary burr formation that take place at high engagement, which are not considered by EOS. In addition, the decoupling of the chip formation and burr formation processes implies that EOS does not have a significant effect on burr formation at high radial engagement. EOS, in essence, is based on the assumption that a chip forms at tool exit without plastic deformation of the workpiece.

Burr Morphologies

In face milling, high radial tool engagement condition produces any of the following burr morphologies at the machined surface: (1) knife-type or uniform, (2) wave-type, and (3) secondary burrs. Photographs of knife burrs are shown in Figure 11. Knife burrs are the largest burrs encountered in face milling. They are characterized by uniform height and a thickness that is small relative to their height, which gives them a laminar appearance. Wave-type burrs are believed to have the same formation mechanism as knife burrs, but are slightly smaller and do not have uniform height (Figure 11). Secondary burrs at high engagement are generally not periodic with respect to the feed marks on the machined surface, and their size is often one order of magnitude smaller than knife or wave-type burrs (primary burrs).

Mechanism of Formation

Little work has been conducted on the formation mechanism of knife and wave burrs. Kishimoto et al. (1981), Chern (1993), and Trommer (1997), described the formation mechanism of knife burrs as a cumulative rollover process of the chip upon exit. However, this model provides no explanation to the uniform height of knife burrs and their formation under tool entrance conditions –at in-plane entrance angles that may be as high as 260° in ductile materials (Figure

5). Hashimura and Dornfeld (1999 b) noted that uniform burrs are formed thanks to cumulative leaning of the transition material that is pushed by the tool flank during each successive pass. The cumulative burr formation mechanism under tool exit condition is presented in Figure 7. The schematic shows that burr formation and chip formation are two separate processes: the exit burr forms as plastically deformed transition material is leaned down towards the machined surface, as opposed to rollover of the chip. The ability of the back-up material to carry the cutting forces controls the burr and chip formation processes. Figure 8 shows how this ability varies with in-plane exit angle. The amount of backup material decreases as radial engagement is increased, hence the cumulative burr is more likely to occur. The exit angle at which the wedge of transition material ahead of the tool begins to plastically deform depends upon material properties (stiffness and ductility) and cutting forces (affected by rake angles and feedrate, etc.). Figure 9 shows how chip formation ceases before the tool exits the workpiece thanks to deformation of the wedge of transition material.

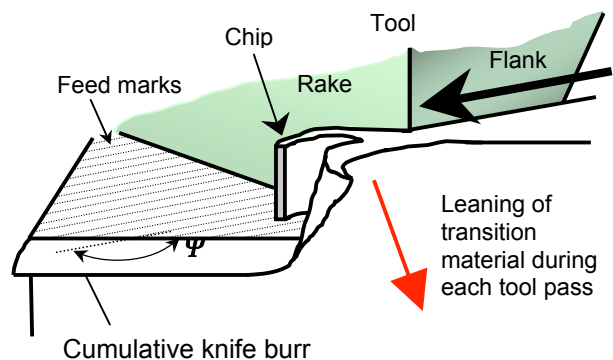


FIGURE 7. FORMATION MECHANISM OF CUMULATIVE TYPE EXIT BURR (AFTER HASHIMURA AND DORNFELD, 1999 b).

The cumulative deformation of the transition material explains the uniform height of the knife burrs, which is approximately equal to the depth of cut. Likewise, it explains the formation of knife burrs under tool entrance condition. It can be observed from Figures 7, 8 and 9 that if the direction of cut is reversed to obtain entrance condition, leaning of the transition material by the flank still occurs.

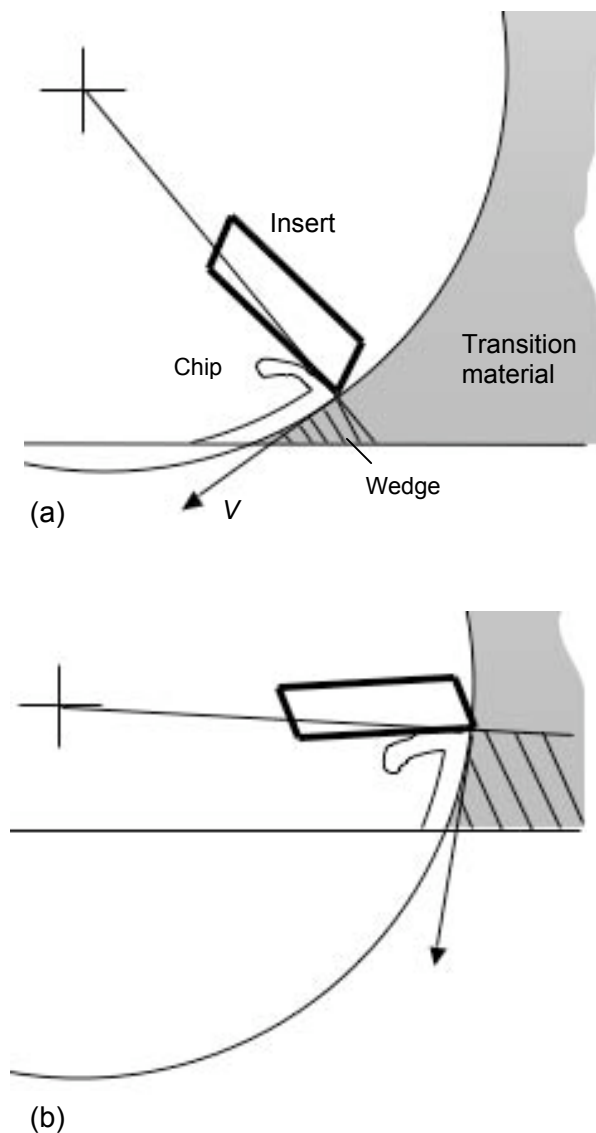


FIGURE 8. DEPENDENCE OF BACKUP MATERIAL AHEAD OF THE TOOL ON RADIAL TOOL ENGAGEMENT (a) TOOL APPROACHING MAXIMUM ENGAGEMENT, THIN WEDGE OF TRANSITION MATERIAL SUPPORTS CHIP FORMATION. (b) AS ENGAGEMENT DECREASES, THE AMOUNT OF BACKUP MATERIAL INCREASES.

Transition from primary to secondary burr formation occurs when the burr leans preferentially towards the transition material and breaks off from the machined surface. In this case, a side burr is formed instead of an exit or entrance burr. In ductile materials the

morphology of primary burrs changes from knife-type to wave-type before the onset of secondary burr formation. Figure 10 shows milled slots on an Al 6061 bar where the tool is stopped at different engagement values. In this case, no knife burrs are formed because the material detached from the machined surface. Secondary burrs are formed from tearing of the transition material; this explains the non-periodicity (with respect to tool marks) of secondary burrs at high radial tool engagements.

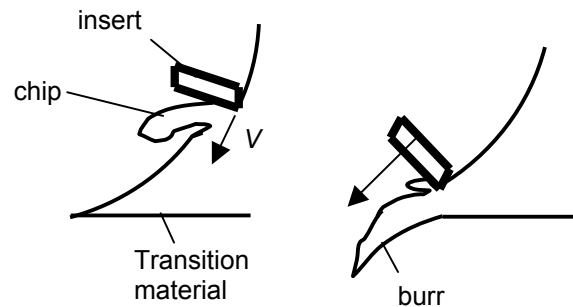


FIGURE 9. CUTTING AND BURR FORMATION PROCESSES.

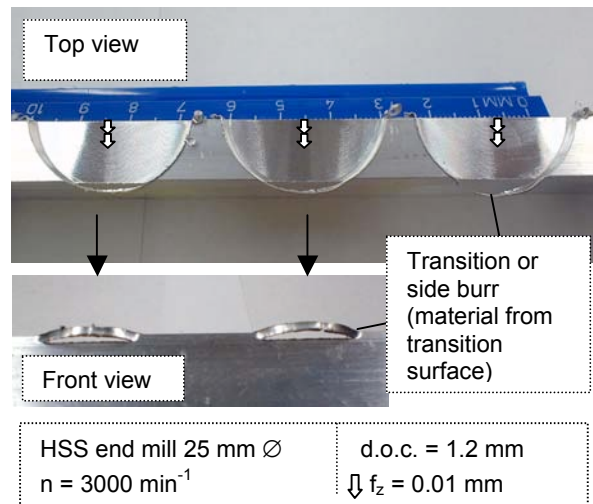


FIGURE 10. DETACHMENT OF PLASTICALLY DEFORMED TRANSITION MATERIAL FROM MACHINED SURFACE AND FORMATION OF SECONDARY BURRS. MATERIAL: Al 6061.

EFFECT OF CUTTING PARAMETERS ON PRIMARY TO SECONDARY BURR FORMATION: BURR MINIMIZATION STRATEGIES

Burr minimization at high radial engagement conditions focuses on the generation of secondary burrs at the widest range possible of in-plane exit angles. Under this circumstance, feasible offset regions for path planning can be made less restrictive around small features such as pockets. An understanding of the effect of cutting conditions on primary to secondary burr transition is key to the prevention of primary burrs at high radial tool engagement conditions.

In-Plane Exit or Entrance Angle

Keeping all other cutting parameters constant, a reduction of Ψ below 180° for tool exit condition, and an increase of Ψ above 180° for tool entrance condition facilitates primary to secondary burr formation (see, for example, Olvera and Barrow, 1995; Avila, 2003). The critical Ψ at which the transition from primary to secondary burr depends on material properties, depth of cut, feedrate, cutting speed, rake angles, lead angle, and nose radius.

Material Ductility

It has been found that material properties have a strong effect on burr formation at high radial engagement conditions (Avila, 2003). The radial engagement at which primary to secondary burr formation occurs increases with decreasing material ductility. Burr morphology distributions as a function of Ψ obtained from three Al-Si alloys are compared in Figure 11. On AlSi9Cu3, primary burrs are observed only in a limited range of Ψ close to 180° because this alloy is relatively brittle. Next in the ductility scale, AlSi7Mg-wa has primary burrs at lower engagements than the previous alloy. The most ductile material, AlSi7Mg-Sr (grain refined by heat treatment and alloying with strontium) presents primary burrs in a much wider range of engagement than the other alloys.

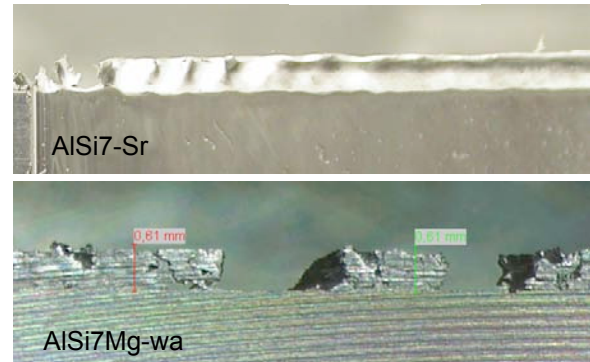
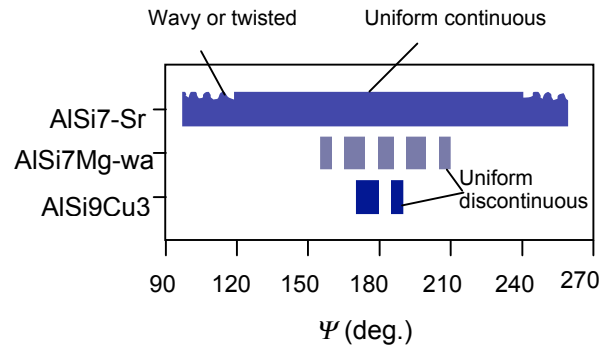


FIGURE 11. EFFECT OF MATERIAL PROPERTIES ON PRIMARY BURR DISTRIBUTION AND MORPHOLOGY.

Depth of Cut

Many studies have found that primary to secondary burr transition is sensitive to in-plane exit angle and depth of cut (Kishimoto et al., 1981; Chern, 1993; Olvera and Barrow, 1995; Trommer, 1997; Avila, 2003). Trommer (1997) performed milling tests on low carbon steel and recorded the critical depths of cut of primary to secondary burr transition at different in-plane exit angles. He found that the critical depth of cut increases monotonically with in-plane exit angle. This is explained by the fact that at higher depths of cut, the transition material is less likely to lean towards the machined surface to form primary burrs. Similar behavior has been observed in Al alloys (Chern, 1993; Avila, 2003). Primary burr formation at high radial tool engagements is reduced by increasing the depth of cut. However, surface finish worsens when depth of cut is increased. The maximum depth of cut that can be used will be limited by the surface roughness requirements of the application.

Uncut chip thickness

It has been observed that an increase in feed per tooth within the range used in finishing operations (0.05 – 0.2 mm/tooth) has a slight effect on the primary to secondary burr transition. For example, Trommer determined that the critical depth of cut on low carbon steel increases from 0.75 mm to 1 mm when feed per tooth is increased from 0.05 to 0.2 mm. Results by Avila on Al-Si alloy show that when using a tool path normal to the edge and constant feedrate, primary burrs may appear at in-plane exit angles that approach 90° because uncut chip thickness (cutting width w , Figure 6) becomes very small in these areas, and hence cutting is more difficult and plastic deformation is favored. Verification tests carried at variable feedrate that maintain constant cutting width along the edge did not produce such burrs.

Rake angles

Positive rake angles affect cutting forces and consequently the degree of plastic deformation of the transition material ahead of the tool. In the same study, Trommer reported that an increase in axial rake angle leads to a decrease of the critical depth of cut at which the primary to secondary burr transition takes place, facilitating secondary burr formation over a wider range of engagements and depths of cut. With regards to radial rake angle, although no comprehensive study is available, it is believed that positive radial rake angles have the same effect due to the decrease in cutting forces associated with positive rake angles.

Lead Angle and Nose Radius

The only study on the effect of nose radius on burr formation in face milling was carried by Olvera and Barrow (1998). They determined that for large nose tool radiuses, primary burrs are produced in a wider range of depths of cut and an radial tool engagements. Figure 12 illustrates the effect of nose radius and lead angle on the formation of the leaned primary burr. Large nose radii and acute lead angles promote leaning of the transition material ahead of the tool towards the machined surface and hence formation of primary burrs.

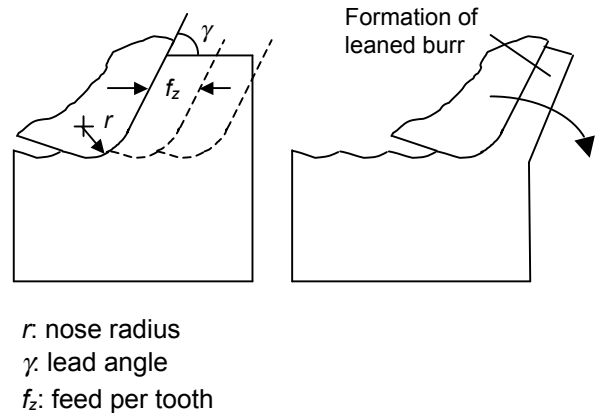


FIGURE 12. HIGH NOSE RADIUS AND ACUTE LEAD ANGLE PROMOTE FORMATION OF LEANED PRIMARY BURR.

Cutting Speed and Absolute Feedrate

Studies on burr formation in face milling have demonstrated that high-speed machining significantly reduces burr size on low carbon steels (Olvera and Barrow, 1998) and in Al alloys (Avila, 2003). Trommer (1997) determined that on low carbon steel an increase of cutting speed from 200 to 300 m/min does not affect the the critical depth of cut of primary to secondary burr transition. However it is expected that, especially on Al alloys, high-speed machining induces less plastic deformation ahead of the tool thanks to the reduction in cutting forces.

Although no studies are available, it is suggested that absolute feedrate of the cutter has an impact on the primary to secondary burr transition. It seems logical to suppose that the speed at which the transition material ahead of the tool is plastically deformed to form either primary or secondary burrs has an effect on the type of burrs formed. Hence a variation in the number of inserts of the cutter may have an effect on burr formation.

Direction of Tool path

Very little work has been conducted on the effect of the feed direction with respect to the edges being machined. Trommer (1997) reported that a variation of the gradient of Ψ (gradient is a function of the feed direction and tool diameter),

from positive to negative gradients, produces a very slight shift of the critical Ψ for primary to secondary burr transition.

CONCLUSION

Burr minimization at high radial tool engagement conditions in face milling centers on the selection of process parameters that generate secondary burrs is the widest range of engagements possible. This enables the use of shorter tool paths over small features such as pockets while still satisfying edge quality requirements. It was determined that the following factors have a significant effect on primary to secondary burr formation: in-plane exit or entrance angle, depth of cut, material properties (ductility), uncut chip thickness, nose radius, lead angle, axial rake and radial rake angle, cutting speed, and absolute feedrate. Further study is required to understand the effect of the radial rake angle, cutting speed, and absolute feedrate on the primary to secondary burr transition.

ACKNOWLEDGMENT

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