BACK CUTTING AND TOOL WEAR INFLUENCE ON BURRS IN FACE MILLING – ANALYSIS AND SOLUTIONS

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ABSTRACT

Back cutting is a special condition that occurs when there is tool run-out, uneven tool wear on the inserts or machining over the same region in opposite directions in two different passes. As the tool progresses along a tool path the instabilities mentioned might cause the back half of the cutter to machine the workpiece. This condition is commonly referred to as back cutting. The most common way of observing the presence of back cutting is the reversal in the direction of tool marks. A series of experiments were performed to gauge the actual effect on process performance due to back cutting. The results surprisingly showed that back cutting does not have a serious impact on the burr formation. Pictures of burrs under an optical microscope shows that back cutting do not create burrs but merely machines over the burrs created from forward cutting. Experiments performed with different back cutting depths produced identical results.

The study also revealed that the tool wear which causes nose rounding is the more significant cause of burrs not explained by prediction theories. Two different strategies, tool geometry based and tool path based are proposed to avoid kinematic conditions that promote burr formation with worn tools. The results from these strategies are presented at the end of this paper.

INTRODUCTION

Face milling is used to generate flat surfaces with well defined edges. The sharpness and flatness requirements are normally dictated by the functional needs. Burrs on these edges are a cause of concern. The burrs tend to get larger and thicker with tool wear resulting in frequent tool changes. Burr formation studies have focused on modeling, control and minimization. The early burr formation models focused on a maximum value of depth of cut coupled with exit angle (Narayanaswami, 1997). EOS brought new understanding based on the kinematics of insert or cutting tooth at the edge (Kumar, 2003). Control charts and Bayes theory was used to identify process parameters that would control the burr size which could then be easily removed by deburring (Kim, 2001). Special tool path schemes and tool geometry were designed for minimization of burrs based on avoiding tool exits (Chu, 2001).

Recent observations from machining with worn tools have shown that the models for burr prediction seem to fail under a specific set of conditions. Back cutting is undesirable because it generates bad surface finish in addition to changing the specified lay direction. This paper attempts to provide theoretical explanation for the same and changes necessary for the tool path planning algorithm developed at Berkeley.

NOMENCLATURE

Face milling cutter, also referred henceforth as milling cutter, cutter or simply tool, can be divided into two regions. The front half of the cutter which normally machines the part when the face is milled is called the toe section of the cutter. The back part of the cutter which normally grazes the surface generating cross hatch marks during level machining is called the heel of the cutter. These are detailed in figure 1. Three different style of face milling can be employed. Tilting the cutter forward it can be ensured that the toe region of the cutter alone machines the workpiece providing a forward lay pattern. This is called forward cutting. Reversing the tilt, the heel region performs significant machining task, leading to backward cutting. Level cutting is the condition that exists when the whole cutter, toe and heel region, play a role in surface generation. Level cutting generates crosshatch pattern. Toeing and Heeling of the cutter is generally employed to reduce the total travel of the cutter without plunging or produce designed lay pattern.

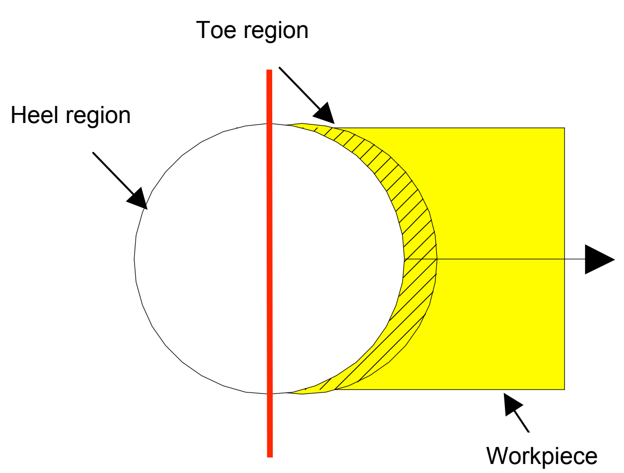

FIGURE 1. REGIONS OF FACE MILLING CUTTER.

EXPERIMENTAL SETUP

The objective of the current experiment is to observe burr formation under the three previously specified styles of face milling. This can be accomplished in various ways; tilting the workpiece, titling the spindle or tilting the tool path. Tests were performed by tilting the tool paths, or machining with a gradient. The lower end covers the condition that normally occurs during run out and the higher value is closer to the Rt value to ensure that new material surface is created uniformly across the workpiece. The three tool paths that generate forward, backward and level cutting are shown in figure 2. Gradient is applicable only for backward cutting. A OKK CNC horizontal machining center was used for this purpose. Worn PCD inserts from the plant were used for making these tests.

The entrance and exit burr formation are observed under these three conditions. Tool entrance occurs when the cutting edges move inside the workpiece while removing material. Exit is the reverse condition when the cutting edges move out of the workpiece while removing material [Reference]. The tool path is designed such that one edge of the workpiece is under tool entrance while the second edge parallel to the first edge experiences tool exit. This is shown in the top view in figure 2. An offset value of 22mm is employed for both entrance and exit side. This was selected as it yielded the largest burrs in previous experiments conducted.

Details of cutting conditions and worn cutter employed are shown in table 1.

TABLE 1. EXPERIMENTAL CONDITIONS.

diameter	63mm
depth of cut	2mm
speed	9525 rpm
feed	0.15 mm/tooth
gradient	10, 40 and 70 microns/diameter

EXPERIMENTAL RESULTS

Normally tests and experiments are performed under level cutting conditions. Burr formation

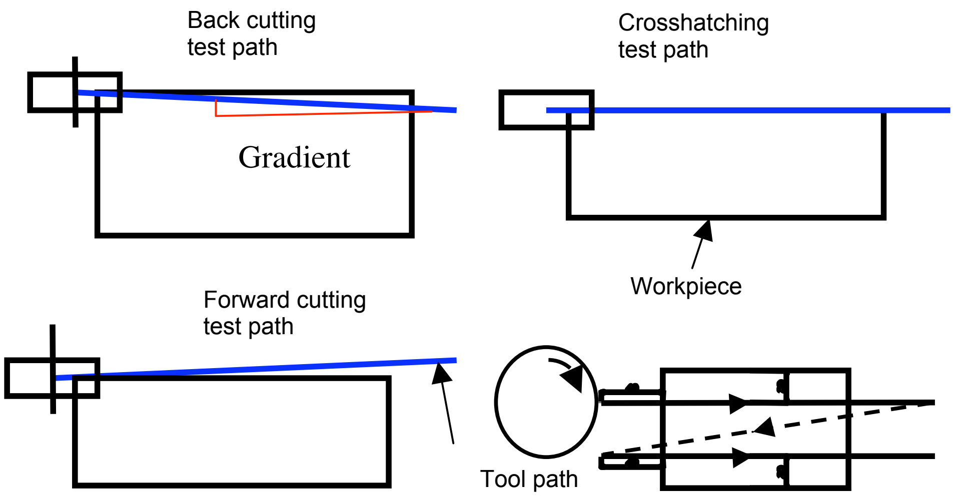

FIGURE 2. EXPERIMENTAL TOOL PATHS.

and minimization theories have been developed only for these conditions. The latest burr prediction theory based on exit order sequence, a kinematic occurrence, has shown that an offset of 22mm and depth of 2 mm would produce significant exit burrs. Previous experimental results and analysis also showed that entrance region is burr free under these conditions. For forward cutting, same results are expected and observed. Back cutting, if present, switches the entrance and exit regions as the edge that experiences entrance condition due to toe section of the cutter will be replaced by exit conditions during machining with the heel section.

The first set of experiments employed forward cuting, back cutting at 10 and 40 micron and level cutting of a rectangular aluminum silicon alloy workpiece. The burr heights for entrance and exit sides are shown in figure 3. Figure 4 shows burr thickness, both entrance and exit, for those conditions as well. It can be observed that there is very little difference between burrs formed during forward cutting and those formed during backward cutting with various gradients or level cutting. All the above conditions have burrs in entrance conditions as well. This was previously attributed to exit like conditions caused by back cutting during entrance. These results clearly demonstrate that the abnormality is not due to the back cutting but other reasons which are explored in the latter sections.

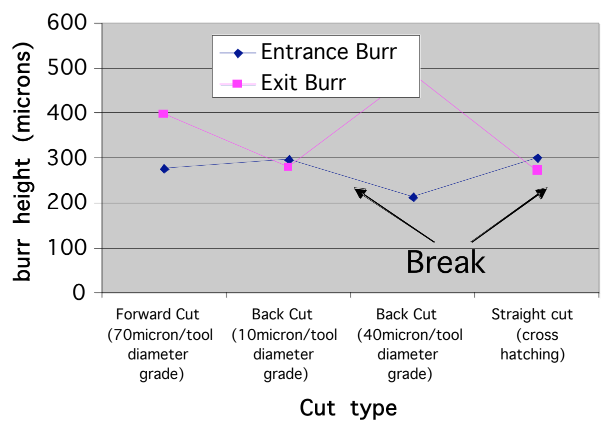

FIGURE 3. BURR HEIGHTS FOR DIFFERENT CUTTING CONDITIONS.

Burr thickness is measured in the direction perpendicular to the direction of burr height. It can be seen that the entrance and exit burr thickness are also independent of the region of cutter doing the final cut. If the conditions had been reversed during back cutting the burr thickness in the entrance region would be more similar to exit burr from level cutting rather than the entrance burr thickness observed during the forward cutting experiments. This clearly demonstrates the fact that the burr formation is not severely affected by back cutting that is normally present during tool runout or tool direction change in tool path or double passing. Further experimental proof is presented at the end of this chapter.

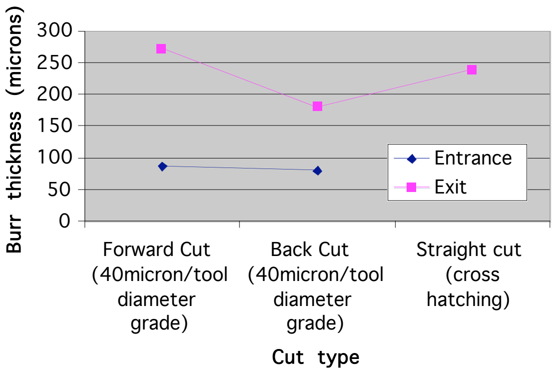

FIGURE 4. BURR THICKNESS FOR DIFFERENT CUTTING CONDITIONS.

IMAGE ANALYSIS

Observing the tool marks and magnified images of the edge condition provides a better insight into the underlying mechanisms. Pictures taken using an optical microscope show that the burr formation, both entrance and exit, is nearly the same for all styles of cutting (figure 5). By observing the images and looking at the burr height and thickness data it can be concluded that burr formation is not extremely dependent on the style of cutting.

Exit Burr

The exit burrs are shown in figure 5 (a) for the three modes of cutting. The regioins can be clearly recognized by the tool marks; the tool moves from top of the picture down rotating clockwise. The burr sizes are recognizably similar. The break outs shown for level cutting also had burrs of same height along the edge.

Entrance Burr

The burrs formed during entrance are however unanticipated. Magnified view of entrance burr during forward cutting under an optical microscope shows clear tool marks on the burr. It can be concluded that burrs form ahead of the cutter and are machined during the next feed step in the direction of feed motion causing these feed marks observed on the burrs.

Observing the magnified image from back cutting experiments it can be seen that the burrs have a distinct cut in the forward direction; though predominantly burrs have tool marks in the backward cutting direction showing that they were formed before the backward cut. This shows that the backward cut merely grazes over the burrs formed during the forward cut.

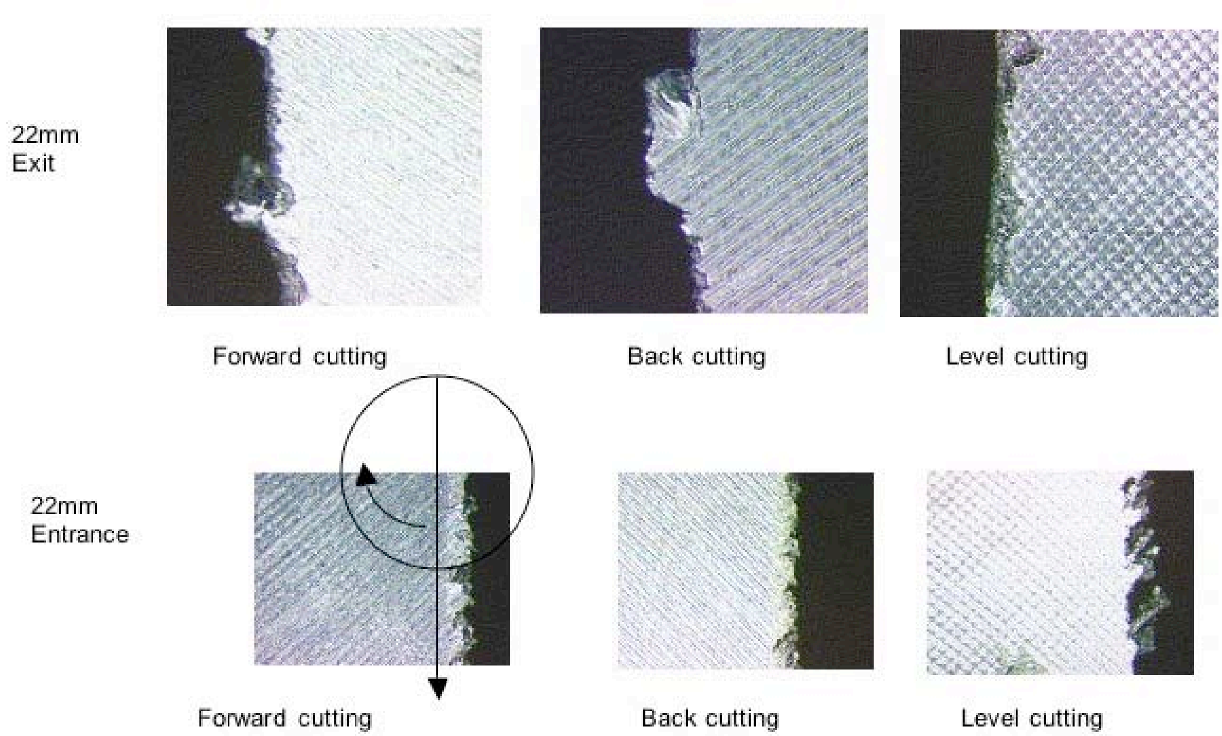

FIGURE 5. EDGE GEOMETRY FOR ENTRANCE AND EXIT.

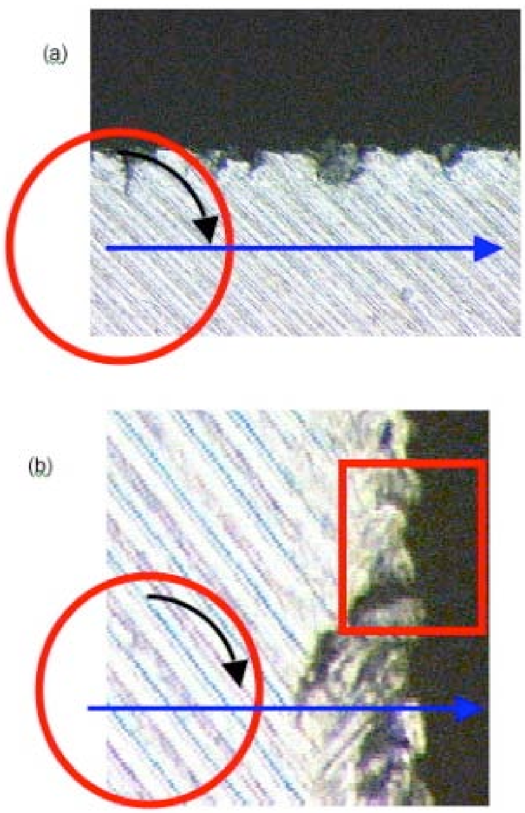

FIGURE 6. MAGNIFIED VIEW OF ENTRANCE BURRS DURING FORWARD AND BACKWARD CUTTING.

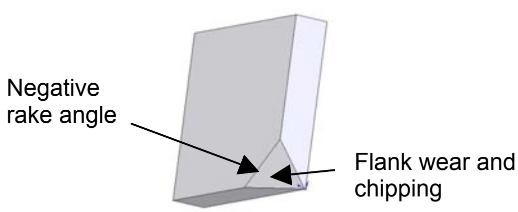

FIGURE 7. MODEL OF WORN INSERT.

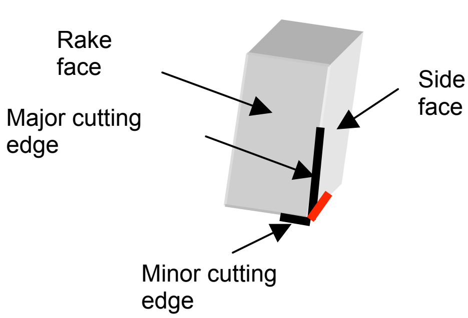

FIGURE 8. INSERT NOMENCLATURE.

TOOL WEAR AND ENTRANCE BURRS

It can be concluded from the previous analysis that the burrs are formed by the tool ahead of the cutter during the entrance stages. The lower burr thickness (figure X) shows that the cutting forces are lower during the entrance burr formation. In addition, this condition occurs only when worn tools are used. New tools do not produce any burrs in entrance. This shows that there is a strong correlation between the exact cutting tool geometry encountered by the edge during entrance and the burrs. Minor cutting edge and minor cutting edge cuts the material during milling operation by plastically deforming the material producing chips.

The first point of contact in major or minor cutting edge is determined by the axial and radial rake angles, lead angle and the offset during engagement. Tool wear occurs naturally with machining leading to increase in burr size. The primary mechanisms of tool wear in milling inserts are described in Gu's paper []. The final geometry of worn insert can be approximately modeled by a plane which produces negative rake angle. High offset value would mean that this region the material would have an exit normal in the outward direction though the velocity. The direction of the material deformation also means that burrs would be formed ahead of the workpiece.

Effect of offset for worn tools

It is widely accepted that new tools do not produce burrs at entrance and relatively small burrs at exit. Tool wear however creates large burrs on both entrance and exits. However, unlike exit burrs, entrance burrs can be completely avoided by choosing suitable offset while machining. The figure below shows the insert interaction with the workpiece at low and high offset values. The offsets are defined by the distance of the tool path, defined by center of the tool, from the entrance edge of the machined workpiece. The top view of worn tool will appear as a chamfer in the top view and for lighter cuts (low axial depth of cut) can be used to model the tool-workpiece interaction.

The instantaneous deformed material flow direction during machining is determined by the segment of the cutting edge that comes into contact with the workpiece along with the

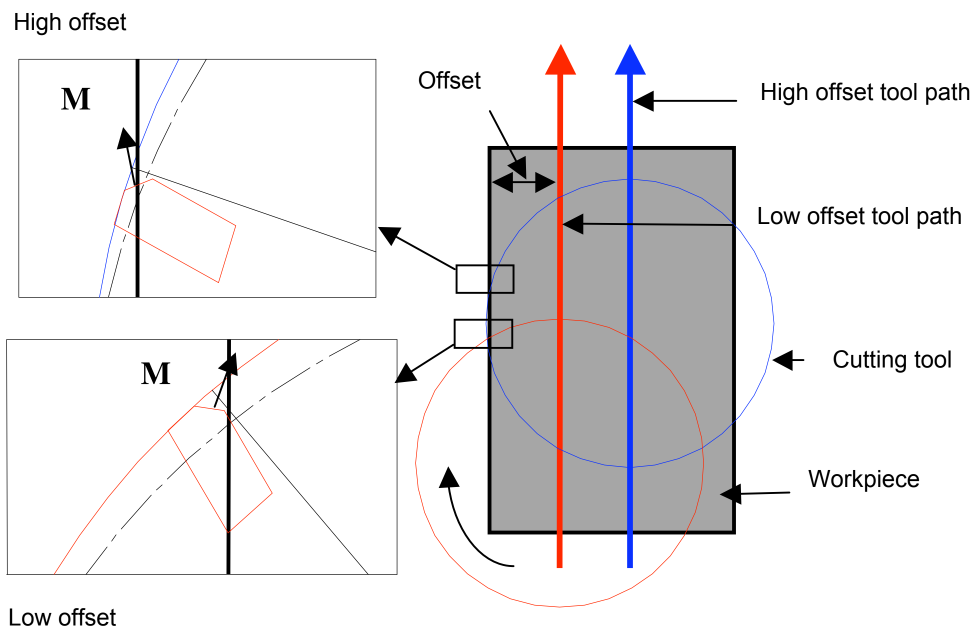

FIGURE 9. KINEMATICS AT ENTRANCE FOR VARIOUS OFFSETS AT 10' RADIAL RAKE.

direction of movement of the cutting edge in contact. Another significant effect of offset is the chip thickness seen by the insert, which is f*sin(θ). The combination of these two effects cause severe burrs for certain conditions as explained below.

The insets on the left show a magnified view of the contact condition during high and low offsets. At low offset, the sharp segment of the cutting edge which has a positive axial rake contact the workpiece and the material flow direction vector represented by **M** is directed into the workpiece there by creating a sharp edge. Increasing the offset gives rise to adverse tool engagement conditions. It can be seen that the top left view shows that the chip thickness is much smaller and the worn segment of tool comes into contact with the workpiece first and the direction of feed cause the material vector to push the material out of the edge causing large burrs.

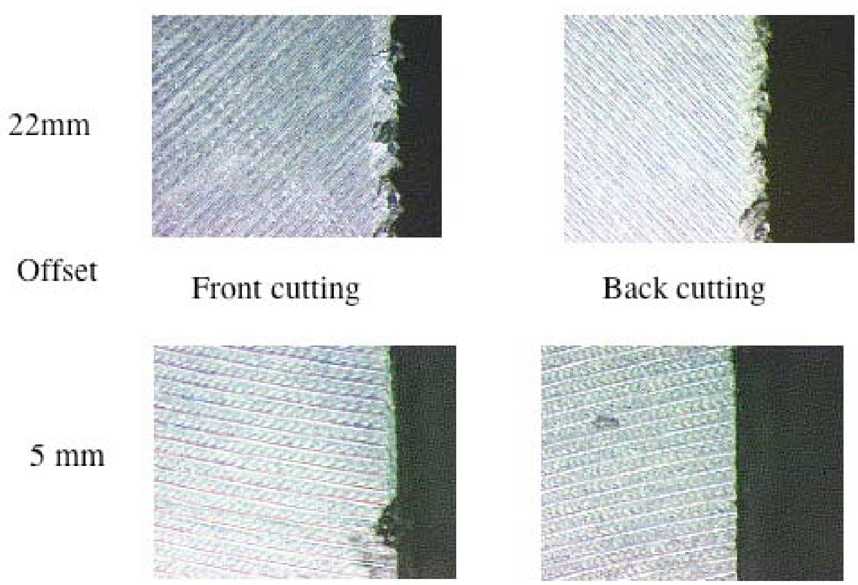

FIGURE 10. EFFECT OF OFFSET ON ENTRANCE BURRS.

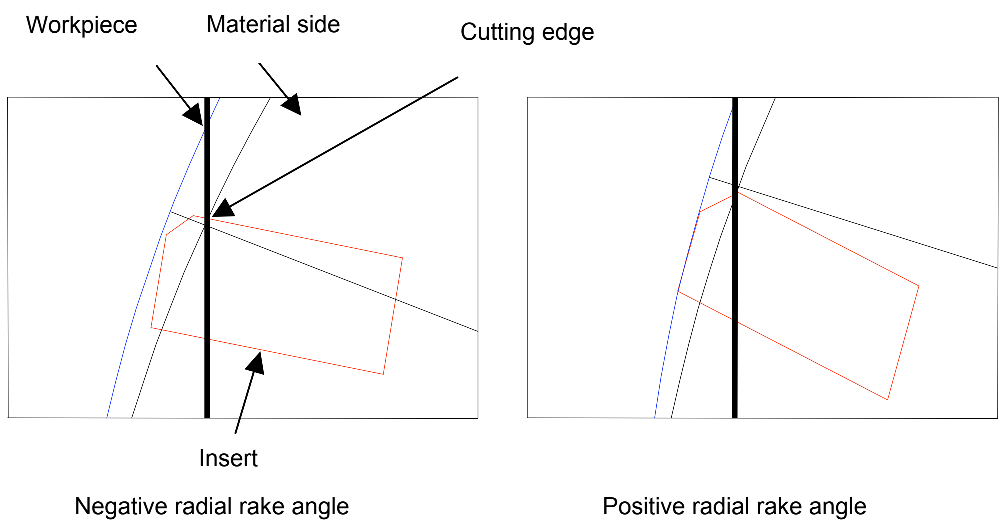

FIGURE 11. KINEMATICS AT ENTRANCE FOR VARIOUS' RADIAL RAKE ANGLES.

Experiments were conducted with the same cutting tool in table1. Figure X shows the difference between cutting with worn tool and controlling the burrs by using smaller offsets. The top row shows the heavy burr formation in entrance for high offsets and the lower half shows the workpiece edge for smaller offset, which remains sharp even with the worn tools. This is also independent of the cutting condition encountered as shown in the figure.

<u>Effect of tool geometry on entrance burrs</u>

Kinematic analysis for various offsets shows that burr formation is dependent on the segment of the tool that makes first contact thereby affecting the material flow direction. In addition to offsets, tool geometry also provides good control over the segment of cutting edge that makes contact and its relative orientation to the workpiece edge. Though offsets are easier to control, sometimes owing to other physical constraints like collision with fixtures or other features of the workpiece other solutions are required. Providing a more open setting or negative radial rake geometry, the sharper section of the cutting edge comes into contact before the chamfer section arising out of tool wear. This ensures that the sharper edge is machining and the material deformation is into the workpiece thereby reducing the entrance burrs. Experiments were performed in aluminum for two cases with 10' and 0' radial rakes when a rib eliminated any changes in offset. The results from going to 0' show that the burrs were completely eliminated even with a worn tool. Figure 3 shows the difference in the picture for high offset value. The degree of opening up of radial rake depends on the offset and wear life that needs to be tolerated.

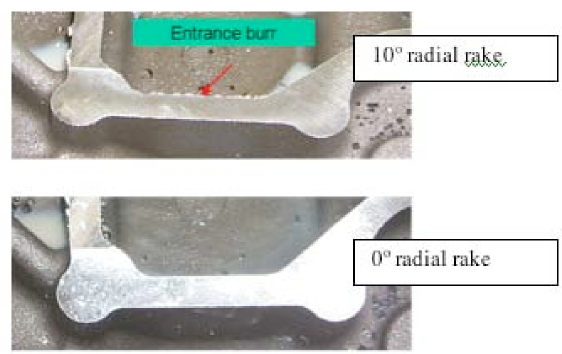

FIGURE 12. ENTRANCE EDGE FOR POSITIVE AND NEUTRAL RADIAL RAKE.

CONCLUSIONS

The experimental observations show that different modes of face milling are shown to have very little effect on the edge quality. Large burrs observed on entrance with worn tools are primarily due to different kinematic engagement rather than back cutting. A couple of different strategies are proposed for eliminating them based on the theory; changing the offset value which is the most effective solution but requires flexibility in planning and reducing the radial rake angle which is effective for highly constrained tool paths. These changes can be kinematically explained using reduced chip thickness and region of cutting edge making the contact. Experimental validation of the solutions is presented to further substantiate the theory.

REFERENCES

Narayanaswami, R., and Dornfeld, D. A., 1997, "Burr Minimization in Face Milling: A Geometric Approach, *Trans. ASME, J. Manufacturing Science and Engineering*, May, Vol. 119.

Kumar, S., and Dornfeld, D.A., 2003, “Basic Approach to a Prediction System for Burr Formation in Face Milling”, *Journal of Manufacturing Processes*, Vol. 5, Iss. 2; pp. 127-143.

Kim, J., and Dornfeld, D.A., 2001, “Cost Minimization of Drilling Operation by a Drilling Burr Control Chart and Bayesian Statistics”, *SME J. Manufacturing Systems*, Vol. 20, No. 2, pp. 89-97.

Chu, C. H., and Dornfeld, D.A., 2000, "Tool Path Planning for Avoiding Exit Burrs”, *J. of Manufacturing Processes*, Vol. 2, No. 2, pp.116-123.

Gu, J., Barber, G., Tung, S, and Gu, R, J., 1999, “Tool life and wear mechanism of uncoated and coated milling inserts”, *Wear*, 225/229, pp 273-284.