Review of geometric solutions for milling burr prediction and minimization

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Abstract: In this paper a review of various methodologies for burr prediction and minimization in face milling is presented. In particular, the authors look into the geometric solutions employed, which typically consist of understanding and modifying tool engagement conditions. The extent of applicability of various approaches is discussed and the possible direction for future research is indicated.

Keywords: face milling, burr prediction, burr minimization

1 INTRODUCTION

Machining, one of the most common manufacturing processes, often leaves burrs along the workpiece edges. The existence of burrs may reduce the fit and ease of assembly, jeopardize the safety of workers during handling, or cause product malfunction in operation. Hence burrs must be removed or avoided. Traditionally, a second finishing operation known as deburring is often used to ensure that the edges produced meet tolerance specifications [**1**]. There are substantial costs associated with the deburring operations. In addition, deburring is difficult to automate and may become a bottleneck in the production line. Lately, there is an emphasis on understanding the burr formation mechanism with a view to minimize burrs: predicting the results of the machining operation, choosing the most desirable cutting conditions, and even modifying the part design.

The burr formation problem has been tackled at design, process planning, and deburring stages. Gillespie and Blotter [**2, 3**], who pioneered burr research, and later Dornfeld [**4**] and Narayanswami and Dornfeld [**5**] extensively addressed the deburring issues, and also looked into the burr formation mechanism and process planning to minimize burrs and facilitate deburring. Stein and Dornfeld [**6**] used burr formation as a process benchmark to present four levels of integration in the design to fabrication cycle of precision mechanical components. Chu [**7**] designed a framework for edge precision machining through CAD/CAM (computer aided design/manufacture) integration, as shown in Fig. 1. Edge quality issues were incorporated at each stage of a product development process including design, macroplanning, microplanning, tool-path planning, and deburring.

In this paper the authors look at different approaches that have been used to address the microplanning stage, which chiefly involves burr minimization through tool-path planning, and the burr predictions stage of this framework. First, the tool-engagement theories that form the geometric basis of the approaches used are explained. In the next two sections the authors explore how these theories have been applied for burr prediction and burr minimization.

2 GEOMETRIC FACTORS IN BURR FORMATION

Burr formation is determined by several factors including (a) material properties, primarily ductility; (b) tool engagement conditions, i.e. workpiece and tool geometry and tool path; and (c) cutting parameters, i.e. feed, speed, and depth of cut. Previous experiments have shown that for a specific material with certain ductility, geometric factors dominate the burr formation [**7**]. Regardless of other machining variables, a number of geometric factors have

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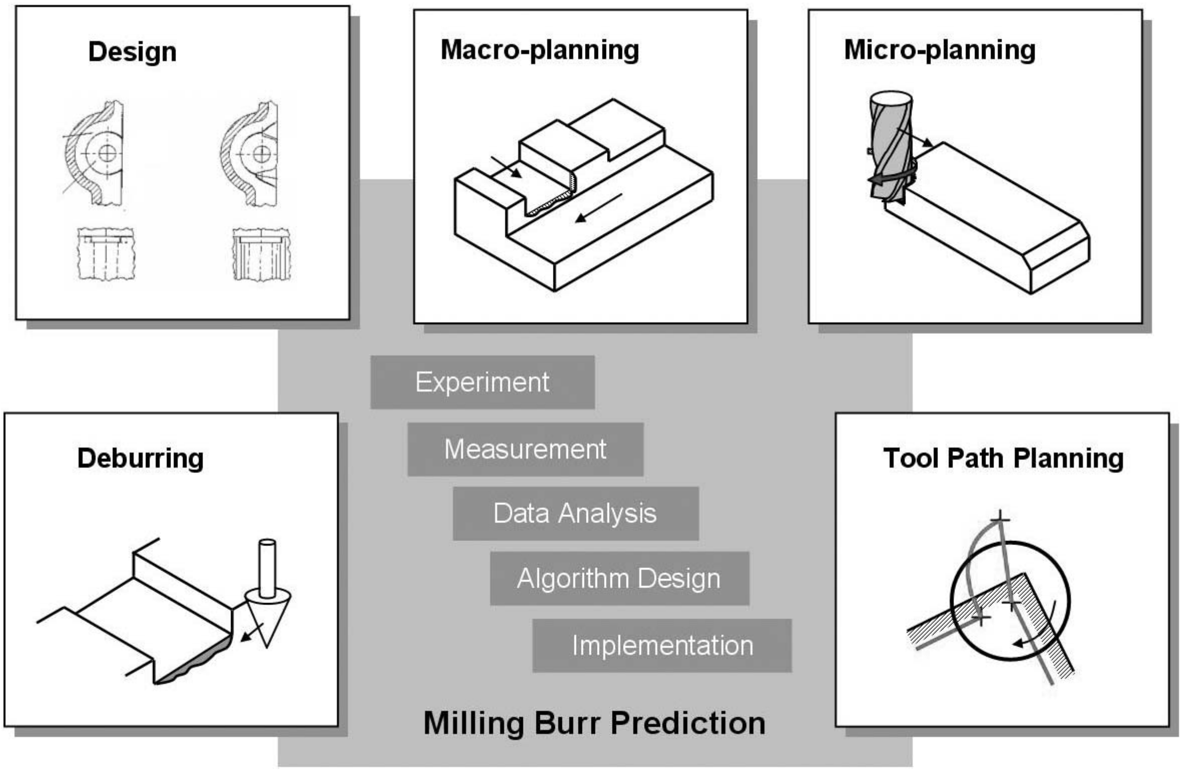

Fig. 1 Framework proposed for edge precision machining [**7**]

been observed in experiments that dominate milling burr formation under normal cutting conditions, factors such as tool exit/entrance, in-plane exit angle, undeformed chip geometry, and tool exit order sequence.

Depending on the size, burrs are classified as primary or secondary [**7**]. The primary burr is much larger in size compared to the secondary burr and is difficult to remove in the deburring operation. The secondary burr is small; it often does not pose a problem and for practical purposes may often be considered burr-free. The primary burr height is proportional to the depth of cut, whereas the secondary burr height remains unchanged, with the depth varying the depth of cut (Fig. 2). The formation of primary burrs has been attributed to the tool engagement conditions by different theories.

2.1 Tool exit theory

According to this theory, if the tool cutter exits the workpiece edge while machining large burrs result, which does not occur when it enters the workpiece edge. Exit here refers specifically to the tool cutting edges moving out of the workpiece at an edge while removing the material. When the tool edge enters the workpiece while removing the material, tool entrance occurs. Entrance burrs do not affect the functionality of the component so much because of their small size and are generally neglected [**8**].

2.2 Tool in-plane exit angle theory

Chern [**9**] found that the type of burr formed is highly dependent on the in-plane exit angle. This angle is defined as the angle between the cutting velocity vector and the free surface of the workpiece, measured on a plane perpendicular to the surface generated by this cutting edge and parallel to the cutting velocity vector, as shown in Fig. 3. Only burrs formed in the cutting direction and over the exit edge were studied. Results from this study showed that there is less burr formation if the in-plane exit angle was less than the critical value, which was estimated at around 120° (Fig. 2).

2.3 Exit order sequence theory

It has been found that the burr formation condition is closely related to the chip flow angle. Unfortunately, precise estimation of the instant chip flow angle is extremely difficult, particularly in the milling operation. However, it can be approximated to a large extent by the insert orientation with respect to the workpiece edges, which corresponds to the tool exit order sequence (EOS) [**10, 11**]. The geometry of a face milling cutter is shown in Figs 4 and 5. An important aspect of the three-dimensional effect is the exit order of the tool edges, as illustrated in Fig. 6 (major cutting edge C, minor cutting edge A, and intersection of two edges B). The exit order of the tool depends on the tool geometry (axial rake

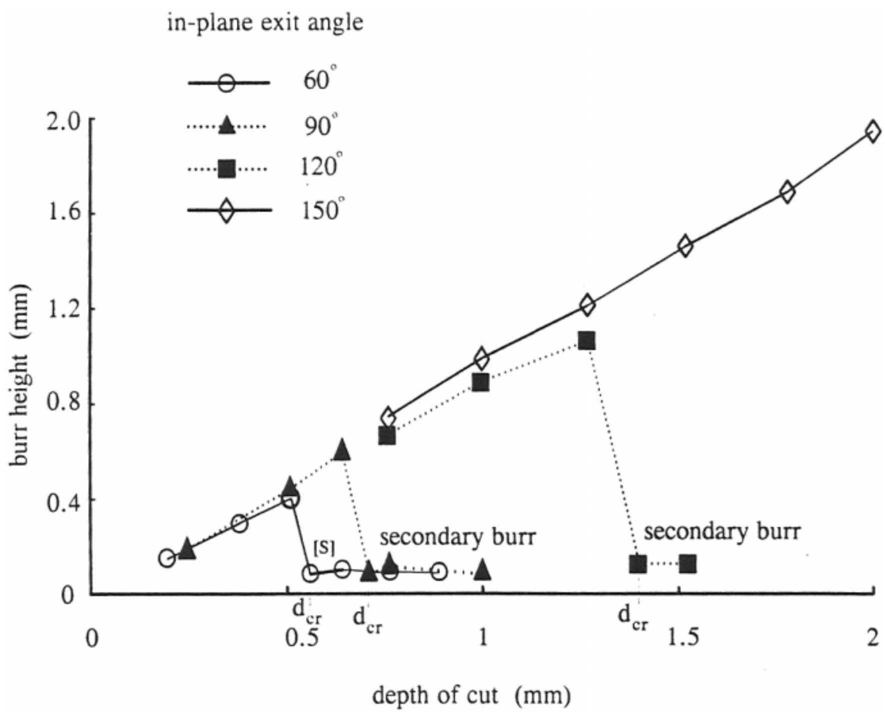

Fig. 2 Variation of burr height versus depth of cut and the exit angle for Al 6061-t6 [**9**]

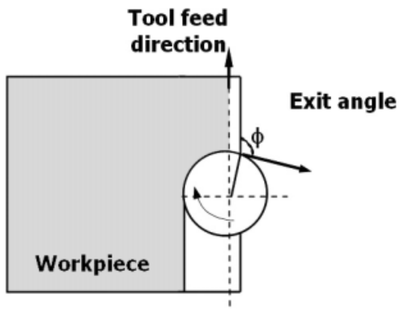

Fig. 3 Tool in-plane exit angle

angle, radial rake angle, lead angle), in-plane exit angle (φ), and the cutting conditions (depth of cut, undeformed chip thickness at the tool exit, which depends on the feed rate, and spindle rotation speed).

For a fixed radial rake angle, as the in-plane exit angle increases the exit order changes from ABC to BAC and then to BCA, in that order. The critical in-plane exit angle, which causes the transition from ABC to BAC and from BAC to BCA, increases as the radial rake angle decreases (Fig. 6). The burr remains near the final exit position of the tool along the workpiece edge. Thus, if only the exit order is considered, exit order ABC results in a smaller burr on the sheared side. If the exit order of the tool edges is CBA then the exit burr on the machined surface edge is expected to be large, because the exit burr is on the hinged side.

2.4 Tool entrance/exit theory

All of the previous approaches assumed that burr formation due to the tool entrance is negligible. However, it has been observed that at very high tool engagement conditions the entrance burrs can be as bad as the primary exit burrs. Rangarajan [**13**] explained this fact using the concept of kinematic entrance and exit. The high feed rates and velocities normally found in high-speed machining changes the classification of regions previously proposed for conventional cutting. In this case, the combined effect of feed and cutting speed turns the velocity vector outside the edge, causing 'kinematic exit'.

3 BURR PREDICTION

The need for a prediction system arises from the fact that information regarding precise location and size of the burrs is necessary for product designers in order to modify the design to avoid burrs at the machining stage. The prediction system can also serve as a process planning tool to help process engineers select an optimal process configuration set to achieve precise edges without the deburring step [**12**]. Different process plans can be compared in terms of burr sizes, locations, shapes, and profile. The burr profile information can further be used in deburring planning. Burr size and its location lead to deburring process selection, while burr size

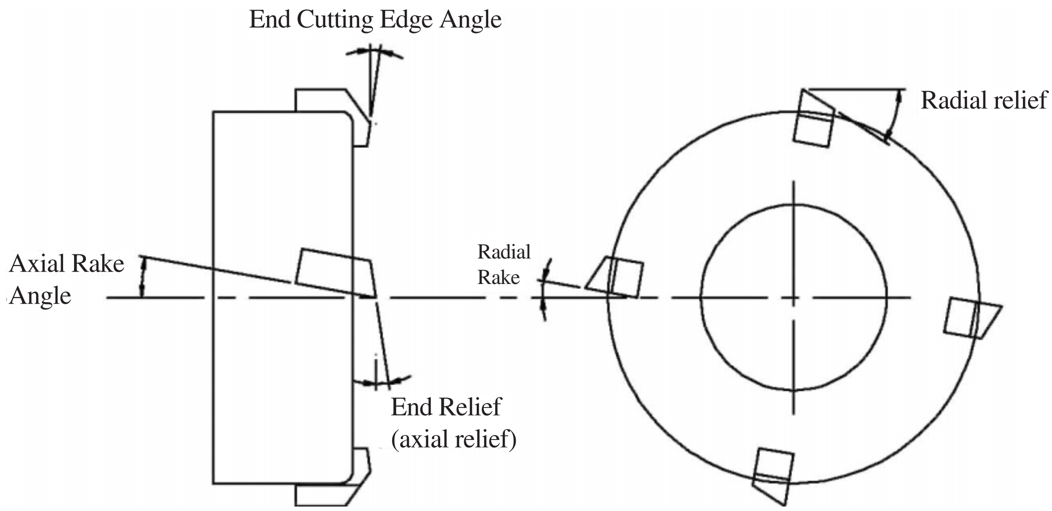

Fig. 4 Face milling cutter geometry

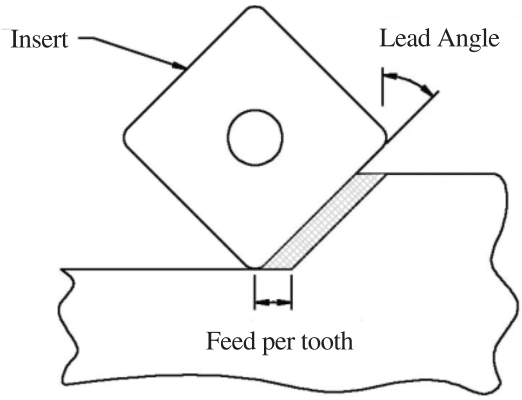

Fig. 5 Face milling cutter geometry: lead angle

violation can warn deburring planners of problematic areas where drastic change in cross-sectional area will take place [**14**].

Sokolowski *et al.* [**15**] used neural networks and fuzzy logic for burr prediction in face milling. The generalization ability of both techniques allows a reduction of data set necessary to build a relationship between the exit angle, cutting parameters, and burr height. However, it was later found that neural networks trained on small datasets are generally not accurate.

Park [**8**] developed a burr control chart that combines experimental data and a probability model to predict the burr type. This analytical model incorporates feed per tooth, depth of cut, in-plane exit angle φ, and its gradient into the prediction of burr type. The burr control chart proposed for use here contains a two-dimensional space constructed by the undeformed chip ratio $C_{r,u}$ and undeformed chip area $C_{a,u}$. Two transition curves divide the two-dimensional space into three regions that correspond to the presence of the primary burr, the wavy burr (transition from the primary to the secondary burr), and the secondary burr respectively. A typical burr control chart is shown in Fig. 7. Based on the experimental data the transition curves are assumed to have the general equation

$$C_{r,u}\sqrt[3]{C_{a,u}^{2}} = \rho_j(\phi)$$

where ρ_j is a constant determined by the in-plane exit angle ($j = 1$ represents the transition curve from the primary to the wavy-type burr, whereas the transition curve from the wavy-type to the secondary burr is represented by $j = 2$). The limitation to this approach is that it does not consider tool geometry while predicting burrs.

Chu [**7**] developed a burr prediction and simulation system, in which, given the workpiece geometry, cutting parameters, and tool path, the system first classifies the workpiece edges according to different burr formation mechanisms obtained in experimental studies. For each edge type, it computes tool engagement conditions for inquiry generation to a corresponding database, in which the burr type is predicted using different criteria. The framework overcomes the limited applicability of each individual experimental finding. This approach is useful to predict the burr type but cannot predict the burr size.

The EOS can be used very effectively to predict milling burrs. In the sequences ABC, BAC, ACB, BCA, CAB, and CBA, going from the first to the last, deformation of the material tends to shift from the transitory un-machined surface to the machined exit surface. In other words, there is increased burr size on the machined surface when moving from left to right because the burr initiation stage keeps shifting away from the machined exit edge and the effect of the roll-over process becomes reduced. It

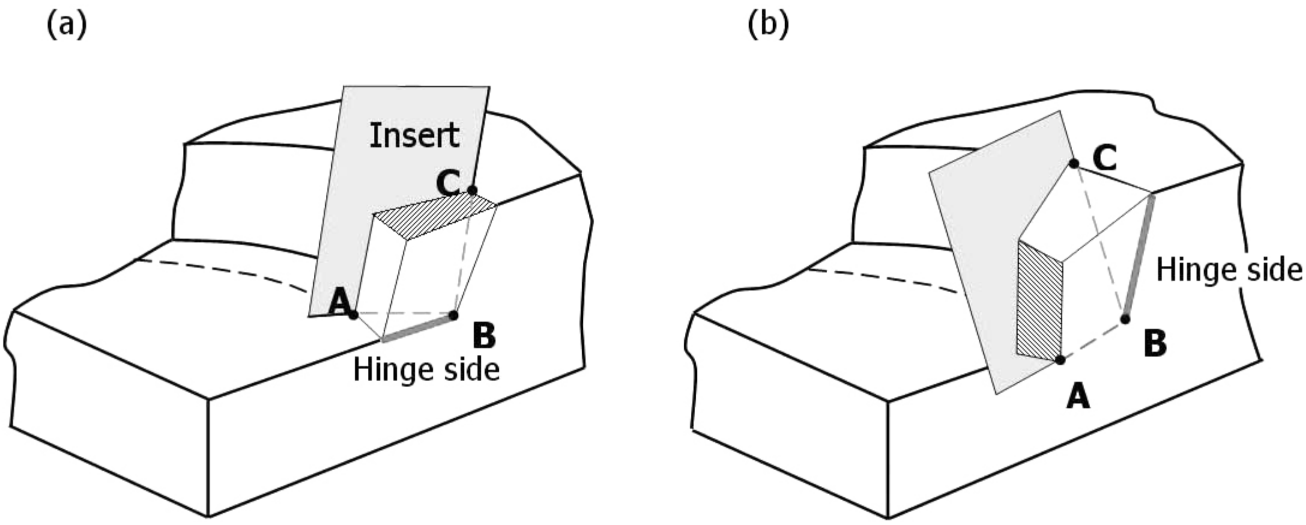

Fig. 6 Tool exit order sequence affects the burr formation condition [**12**]

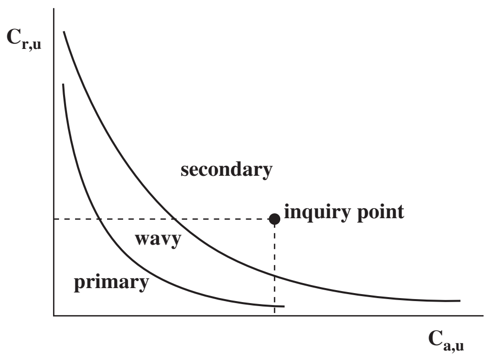

Fig. 7 Burr control chart [**8**]

was observed that though actual burr size varies with different materials, the trend of burr size remains the same with different EOSs [**16**].

Implementation of the EOS was accomplished by tessellating the curved edges into small straight edges. With this approach the algorithm is applicable to any given part geometry and to any given tool path for that part geometry. A fully interactive graphical user interface (GUI), with a solid geometric viewer, has been implemented. A burr size database has also been developed, which quantifies and displays the burr size based on the EOS [**12**]. The prediction using the EOS is limited to exit burrs.

Apart from these theories, numerous burr expert systems have been developed which are based on the experimental studies and are basically database prediction systems. These studies generally involve conducting comprehensive experiments by varying various parameters involved and then finding burr formation patterns based on the results, in order to construct the burr expert systems. These prediction systems have been useful in some instances, especially if the study involved varying only a few parameters, as in the case of drilling. However, for face milling, to fill a database for all the parameters involved is a task of astronomical size, which is very time-consuming and costly [**12**].

4 BURR MINIMIZATION

Tool engagement, to a large extent, determines machining burr formation. Therefore, burr minimization can be achieved by controlling tool engagement conditions. Three main factors affecting how a tool cutting edge leaves the workpiece are: workpiece geometry, tool geometry, and tool path. Usually workpiece design and tool geometry are fixed, so only the tool path can be used for reducing burr formation. The basic approach in geometric solutions to burr minimization has been to avoid tool exits or limit the in-plane exit angle below a given threshold.

The first geometric scheme developed for burr minimization was based on a representation in a CAD framework to parameterize the edges of a two-dimensional polygonal contour into primary and secondary burr zones [**17**]. The algorithm adjusts the workpiece orientation to minimize the primary burrs along the edges of the part, using a variety of objective functions reflective of deburring complexity, such as the primary burr length or the number of edges on which the burr is formed. The primary burr is assumed to be formed when for a given depth of cut the exit angle φ is greater than a threshold value. The exit angle is computed as a function of cutter radius, the angle of approach of the cutter, the cutter centre position and the part edge geometry. This approach assumes that only exit burrs are primary. It considers

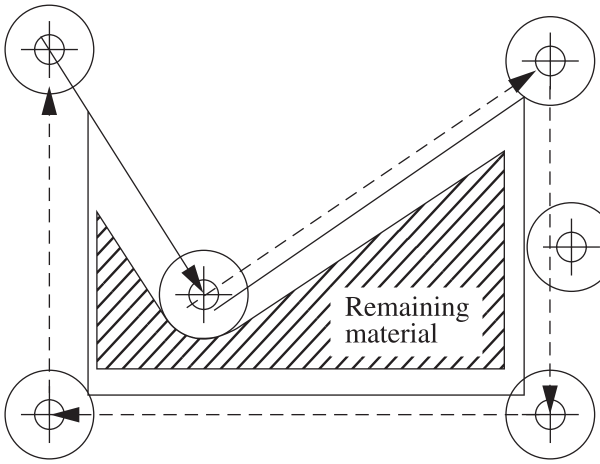

Fig. 8 Window framing [**18**]

only those parts that are smaller than the tool diameter.

Window framing or contour parallel milling (Fig. 8), that avoid exit burr formation, were suggested as a solution to burr minimization [**18**]. This scheme is not generally preferred as it causes deterioration of the surface finish due to unbalanced forces on the tool and also increases the tool-path length considerably.

Chu [**7**] extended the applicability of Narayanswami's approach to multiple tool paths as well as work parts with curved edges and inner profiles. His algorithm discretizes curved edges, generates zigzag tool paths, and estimates the total length of primary burrs formed for each tool path based on the burr-formation criteria. Exit burr minimization is achieved by selecting tool feed directions and simulation of primary burr locations. This approach assumes that only exit burrs are primary. The tool path chosen is very likely to be suboptimal because it considers only zigzag tool paths.

Burr minimal tool-path generation is a more direct approach than testing various tool paths for relative burr length. Chu [**7**] developed two distinct approaches for tool-path planning of two-dimensional polygons. The first approach generates exit-free tool paths by offsetting the workpiece edges with an appropriate width of cut. The second one locally adjusts tool positions on given tool paths, in order to avoid tool exits occurring around the workpiece vertices. He also designed a two-stage algorithm for three-dimensional free form contours. The cutter locations that cause the tool to exit are first detected. Then a heuristic scheme is applied to generate new cutter locations with no tool exits. This scheme assumes that only exit burrs are primary and is limited to workpieces with a single chain of edges.

Exit-free tool paths have been generated in a global manner by offsetting the workpiece edges by Rangarajan [**19**]. He developed a set of geometric algorithms that avoids tool exits in planar milling of two-dimensional polygonal and curved contours. Tool paths are generated by offsetting the workpiece edges with appropriate widths of cut, depending on the edge types (straight or circular), thus allowing the tool always to enter the part. However, the total machining time is increased, since a conventional zigzag tool path has to be applied to remove the remaining material.

Not all edges of a part are critical with respect to the burr problem. Utilizing this fact, Rangarajan [**19**] developed a practical tool-path planning scheme for exit burr minimization, based on assigning priorities to various features that require sharp edges. A detailed algorithm was developed to identify and eliminate burr formation in the most critical edges of the given part. This approach also considers only exit burrs and is applicable only when the tool diameter is smaller than the feature size on the workpiece.

For the local regions of high entrance/exit angles and exit in the feed direction, Rangarajan [**13**] applied a contour parallel milling strategy to those specific regions in order to generate a modified tool path. The tool lifting and re-entry from a suitable location is another useful strategy where a local modification of the tool path is not possible. The location of re-entry is chosen to minimize the increase in length while avoiding plunging.

All of the above geometric approaches for burr minimization tend to increase the tool-path length and thus the machining time significantly. From a feasible set of burr minimal tool paths the shortest path can be chosen using a modified convex hull [**13**].

Due to tight cycle time constraints, sometimes large cutters are used to complete the milling operation in a single pass. As this class of single-pass operations offers very little manoeuvrability, completely avoiding exits is not possible. Ramachandran [**20**] implemented a tool-path planning scheme developed by Rangarajan [**13**] to handle this case. The model derived from the work of Chu [**7**]. This scheme minimizes exits and generates the shortest tool path using the feasible region approach. Special attention is paid to 'push exit', which occurs when the tool tries to push the material out of the workpiece rather than machining it; this is identified and then completely avoided. The algorithm is shown as a flowchart in Fig. 9. This scheme does not guarantee complete machining. It can be applied to a small domain of parts.

Figure 10 shows a sample part, the tool and the tool path generated using the feasible

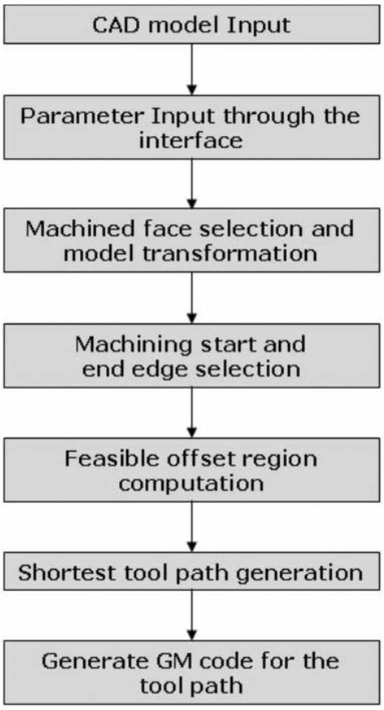

Fig. 9 Feasible region approach algorithm [**13**]

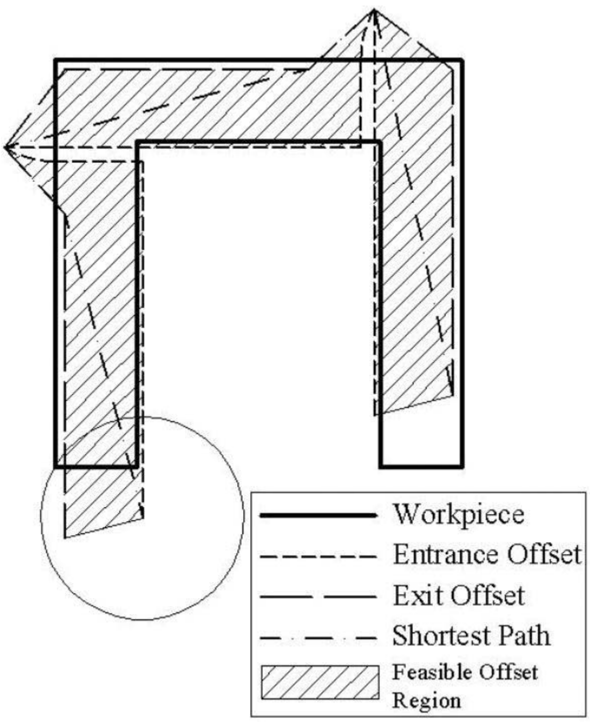

Fig. 10 Burr minimization using the feasible region approach on a sample part [**20**]

region algorithm. The approach uses offset calculations [**21**], local adjustments around corners, and shortest path generation through the feasible region.

5. CONCLUSION

The current work presented a review of the different approaches that are used for predicting and minimizing milling burrs. As is evident from the referenced papers, in recent years there has been a great deal of research activity in this field. Burr formation has been quite well understood and recent research has concentrated more on application of the theoretical foundation for improving edge quality in machining. The trend that is formed encourages more automated system building for micro- and macroprocess planning for burr minimization and integration with existing CAM systems. Recent and more functional methodologies that are presented here have more or less evolved from the earlier ones.

The current tool-path planning approach is limited in application to simple components. Components encountered in the automobile industry are generally more complicated, due to closely located features on multiple surfaces; the feasible region approach often cannot give a burr minimal tool path. Fixtures, adjacent shoulders, and features such as the rib, which are intrinsic to the workpiece, also need to be incorporated as part of collision prevention requirements. There is a need for a comprehensive tool-path planning approach to provide for burr minimization for a broad class of components.

Going back to the proposed integrated framework for burr minimization, there has been little research at level I, i.e. in the design and feature interaction stage. Further, burr prediction can be a very important step in deburring automation, such as for generating an NC (numerical control) code for deburring tool paths, and the choice of deburring tools. Automation of tool size and parameter selection in addition to tool-path planning needs to be attempted in order to accomplish multiple objectives like cycle-time minimization and surface finish requirements, in conjunction with burr minimization.

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APPENDIX

Notation

A	minor cutting edge
B	intersection of two edges B
C	major cutting edge
$C_{\mathrm{a,u}}$	undeformed chip area
$C_{\mathrm{r,u}}$	undeformed chip ratio
ρ_j	constant
φ	in-plane exit angle

