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Linking tool paths generated with different offset distances for edge quality enhancement in planar milling

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Abstract: Edge quality can be effectively enhanced in planar milling by preventing the tool from exiting the work part. This is achieved by planning of tool paths offset from the part edges with appropriate distances. Two consecutive edges may require different offset distances to avoid the tool exit occurring around the joined vertex. Linking such tool paths is problematic and has not been studied. This paper presents a systematic approach to solving this problem. All geometric configurations of consecutive offset edges are recognized, simplified and classified into four groups. Corresponding algorithms consisting of three basic geometric operations (connect, trim, and extend) are developed for each group. The extra paths added in the linking process are analysed and the results show that they do not induce unfavourable end conditions such as sharp turns, over-extended paths or introduction of unexpected tool exits. This work overcomes the deficiency of previous studies and completes the tool path planning for enhancement of machining edge quality.

Keywords: tool path, edge quality, offset, tool exit

NOTATION

$\boldsymbol{c}$	intersection between the first and second offset edges
$\boldsymbol{c}_1$	end point of the extended second tool path
$\boldsymbol{c}_2$	end point of the extended first tool path
d	offset distance
$\boldsymbol{e}$	start point of the uncut region
e_1	first offset edge
e_2	second offset edge
$\boldsymbol{p}_1$	point on the first edge with distance r to the end point
$\boldsymbol{p}_2$	point on the second edge with distance r to the end point
$\boldsymbol{q}_1$	terminated point of the first tool path
$\boldsymbol{q}_2$	terminated point of the second tool path
r	tool radius
$\boldsymbol{s}$	intersection between the first and second tool paths
$\boldsymbol{t}$	tangent point of the tool on the part edge
TP	tool path
w	width of cut
θ	extended angle of consecutive part edges
θ'	extended angle introduced by the extra tool path
θ_1	extended angle of the added tool path and the first offset edge
θ_2	extended angle of the added tool path and the second offset edge

1 INTRODUCTION

Milling is one of the most important machining operations in industry. A variety of milling processes have been developed and employed in different circumstances. In planar or face milling, the cutting tool moves in a plane and removes a layer of stock material. An edge defect is often formed along the edges where the tool rotates out of the part, namely on tool exit. The cutting chip is pushed outwards from the material side at the tool exit and separated from the stock when the material is unable to sustain the stress induced by the tool. The

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chip separation involves shear forces as well as other plastic deformation such as rubbing, compression and tearing. As a result, the separation interface is usually far from a perfect cut, with material in irregular shapes remaining along the part edge. Such residual material is referred to as burr or edge defect in practice [**1**].

The existence of burr may interfere with assembly, jeopardize the safety of workers during part handling or cause product breakdown in operation. Therefore, a secondary finishing operation, known as deburring or edge finishing, is normally required to assure that the machining edge quality meets design specifications. The edge finishing operation is difficult to be automated and the associated costs can be substantial. More importantly, it cannot be performed on certain workpieces such as those from precision manufacturing and micromachining [**2**]. To eliminate the deburring operation, it is advantageous for the formation of the edge defect to be controlled within an acceptable amount during the main machining operation. For instance, a secondary burr is generally much smaller in size compared to a primary burr [**3**] and usually does not pose a problem. Experimental studies [**4**] have shown that the primary burr only occurs at tool exits; thus an effective approach to reducing it is to prevent the tool from exiting the work part so that only a secondary burr has a chance to form. This approach is simply a geometric means and readily implemented through tool path planning or process planning.

Two methods have been developed to avoid tool exits in planar milling by tool path planning. The first method detects the locations at which the tool pushes the material out of the part [**5**]. Geometric algorithms are then applied to adjust these tool positions locally. This method may cause excessive tool engagement, limiting its practicality. The second method analyses how tool exits take place around a vertex shared with two part edges [**6**, **7**]. For generation of tool paths parallel to the part edges, the tool exit can be eliminated by appropriate selection of the offset distance. However, achieving this purpose may result in different offset distances for two adjacent edges. In this case, linking adjacent tool paths is problematic, as unfavourable conditions often occur that either increase the machining time or decrease machining quality [**8**]. Moreover, the tool paths added in the linking process may possibly induce new tool exits. There is a lack of research concerning this path linking problem.

This paper presents a systematic approach that links the tool paths offset from the edges of a polygonal part with different values. All geometric arrangements of such offset edges are recognized, simplified and classified into four distinct groups. Different procedures consisting of three basic geometric operations are applied to each group for the path linking. It is shown that the consequent tool paths do not cause undesirable end conditions such as sharp turns, overextended paths or additional tool exits. This work enables proper linking of the exit-free tool paths generated by the previous algorithms [**6**, **7**], and thus makes the tool path planning a complete solution for edge quality enhancement in planar milling.

2 TOOL PATH PLANNING FOR TOOL EXIT AVOIDANCE

Tool entry and exit conditions determine, to a large extent, edge defect formation in a milling operation. Tool exit refers specifically to one or more of the tool cutting edges moving out of the workpiece at an edge while removing material. Tool entry refers to the tool cutting edges moving into the workpiece at an edge. Tool exit is a necessary condition for primary edge defects to form. Alternatively stated, only secondary edge defects can be formed at tool entry. This observation has been used in planning a tool path for surpassing an edge defect in face milling. There are three distinct tool exit conditions that have to be considered, including (a) the tool entering the part, (b) the tool moving along an edge and (c) the tool encountering an adjacent edge, as shown in Fig. 1. Avoiding the tool exits for the first two conditions is trivial. The third exit condition is more complex. Two methods of tool path planning have been developed to resolve this problem. The first method [**7**] detects the tool position on a given tool path at which the tool starts to exit from the second

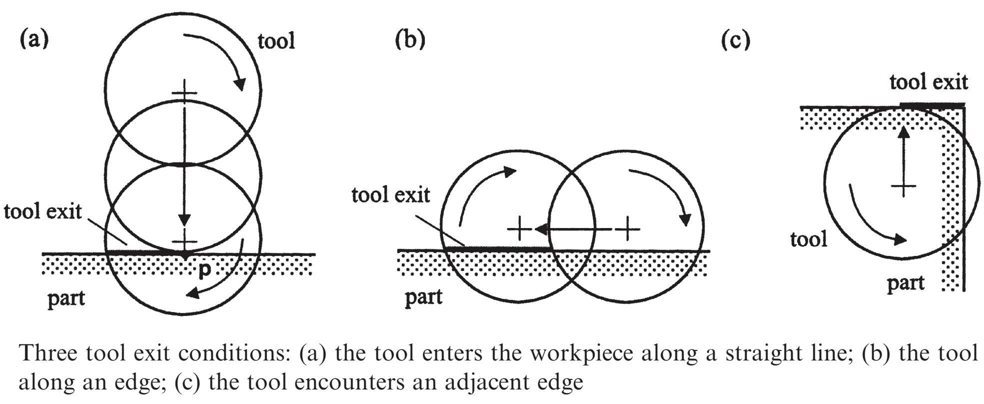

Fig. 1 Three tool exit conditions: (a) the tool enters the workpiece along a straight line; (b) the tool moves along an edge; (c) the tool encounters an adjacent edge

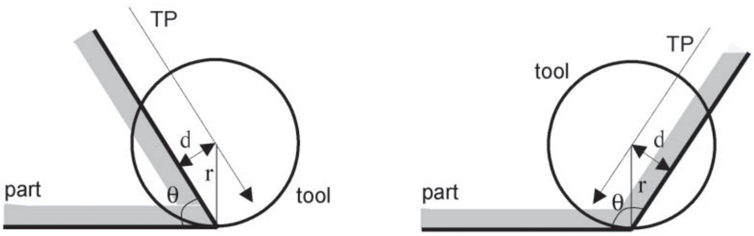

Fig. 2 Tool exits in two-dimensional convex polygonal profiles

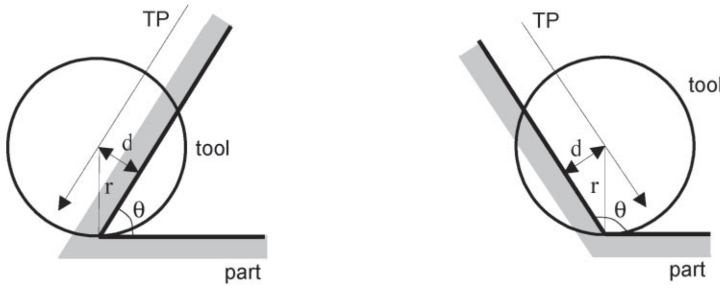

Fig. 3 Tool exits in two-dimensional concave polygonal profiles

edge. Geometric algorithms are proposed to modify the tool path so that the tool always enters the part.

The second method embeds the tool exit avoidance in the generation of tool paths offset from the part edges. The width of cut w, normally a constant value when the tool moves along an edge, and the tool radius r determine the offset distance d, i.e. $d = r - w$. Figure 2 shows the tool position at which the tool exit occurs exactly at the vertex shared with two edges of a convex polygon. In this example, the offset distance is written as

$$d = r \cos\theta \tag{1}$$

where θ is the extended angle of these edges. This equation holds for both acute and obtuse angles. Tool exit starts to form when the width of cut is larger than the critical value in equation (1). Thus the exit-free offset distance range is

$$[d, r] \tag{2}$$

The offset is always smaller than r; otherwise there is no material removal in the milling operation.

A similar analysis can be conducted for a concave polygon. The offset distance causing the tool to start exiting the part is expressed as

$$d = r \cos\theta \tag{3}$$

Notice that θ is measured on the edge opposite to the material side in Fig. 3. The exit-free offset range becomes

$$[-r, -d] \tag{4}$$

The minus sign of the distance indicates that offsetting is towards the material side.

3 LINKING CONSECUTIVE OFFSET EDGES

The offset ranges derived above do not necessarily have an overlap for any two consecutive edges. As a result, the offset distance of the first edge may not be the same as that of the second edge around the shared vertex, as shown in Fig. 4. Linking two adjacent tool paths with different offset distances can be error prone. Adverse

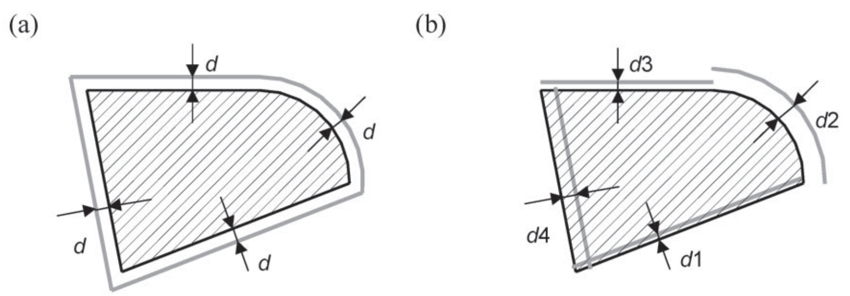

Fig. 4 (a) Two-dimensional offsets with (a) a constant offset distance for each edge and (b) various offset distances

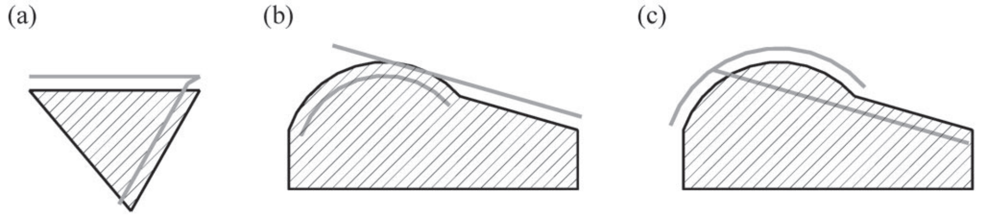

Fig. 5 Poor end conditions in linking offset edges: (a) a sharp corner, (b) disjointed edges and (c) unexpected edge shortening

cutting conditions can occur and a systematic corrective approach is needed. Three geometric operations are proposed to link those tool paths: (a) connecting end vertices, (b) extending the edges and (c) trimming the edges. Any single operation alone is not sufficient to finish the linking process. In addition, unfavourable end conditions may arise while conducting these operations. Firstly, the end points of adjacent tool paths too close to each other will yield a sharp corner, inducing excessive accelerations and decelerations in the tool motion, as shown in Fig. 5a. Figure 5b depicts the occurrence of disconnected path segments when two offset edges are unconditionally extended. On the other hand, such an extension operation sometimes causes unexpected tool path shortening after these edges have been trimmed (see Fig. 5c). It is not guaranteed that the material will be completely removed in this situation. Furthermore, additional tool exits are likely to occur and further deteriorate the edge quality.

The exit-free offset range of a part edge can be categorized into three types: (a) spans over the original part edge, (b) lies inside the part and (c) lies outside the part, as depicted in Fig. 6. The offset range is at only one side of the edge in the last two cases. It should be noted that any offset value within the range generates an exit-free tool path. This fact allows an offset distance within the range to be freely chosen. A number of heuristics are made to exploit this flexibility in the present approach. Firstly, it is assumed that the offset value is zero in the type 1 offset range, i.e. the tool path is identical to the edge. Next, the offset distance in the type 2 and 3 ranges is chosen to be the one with the minimum absolute value.

A few observations can be used to simplify the problem further. Firstly, any transformations consisting of rotation and/or translation can be applied to the part geometry without changing the tool path linking. Secondly, the linking process is not directional, i.e. the sequence of the linked edges can be reversed. These characteristics help to reduce the total number of geometric configurations of adjacent offset edges. Nine distinct configurations are recognized and classified into four groups. The Appendix describes the procedure of deriving and simplifying these configurations. For each group a linking scheme is proposed that modifies the existing tool paths without causing the occurrence of the poor end conditions. Figure 7 demonstrates the operations employed in each group along with the corresponding geometric configurations. Dark lines represent the part edges and the bright lines denote the offset edges in these figures. The non-directionality indicates that every configuration of an external contour has a dual part for the corresponding internal contour, but both internal and external contours can be treated the same. Therefore only external contours will be discussed in this paper.

The remaining task is to show that unfavourable end conditions do not occur with the application of the proposed schemes. The offset edges in scheme 1 have been well connected, requiring no special operations. In scheme 2, the first (TP1) and the second tool path (TP2) must be terminated at $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$ respectively, as shown in Fig. 8. An additional path TP$'$ is added to connect TP1 and TP2, introducing two angles θ_1 and θ_2. The velocity change is reduced in the new tool paths provided that these two angles are greater than the angle extended by the original paths. From the figure it can be seen that θ_1 is equal to the sum of θ and the complementary angle of θ_2, i.e. $\theta_1 + \theta_2 = \theta + \pi$. Since both θ_1 and θ_2 are not greater than π, they must be larger than the angle θ. This conclusion holds for both configurations (3) and (4). The tool path directions

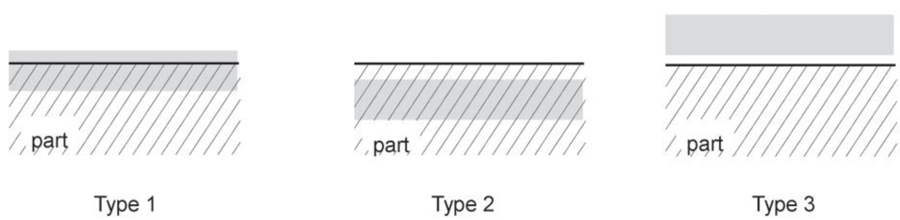

Fig. 6 Three different offset types: span over the edge, lies inside the part and lies outside the part

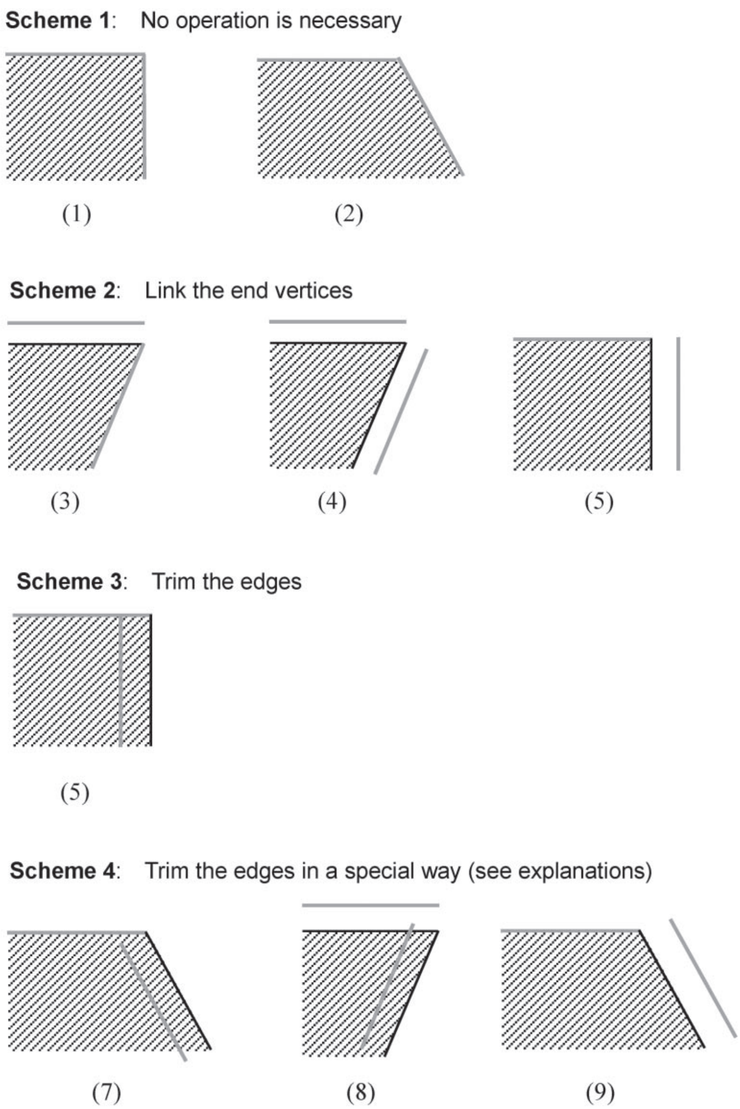

Fig. 7 Configurations of two adjacent offset edges

do not change after the path linking for configuration (5). The authors claim that the results are satisfactory for scheme 2, as the angles introduced do not produce abrupt turns in the tool motion.

In scheme 3, the offset edges are trimmed with no difficulty. However, the same operation loses its practicality when applied to the remaining cases. Figure 9 depicts a poor situation at which unexpected edge shortening is encountered. The tool moves along the first tool path (TP1) until ***s*** makes a turn at the point and then goes on the second tool path (TP2). In this case the tool will not go beyond ***s*** from either path, leaving the region ***ect*** uncut. Imposing the heuristics 1 and 2 ensures that the maximal offset distance of the second edge (e2) equals the tool radius r. As a result, the maximal length of the

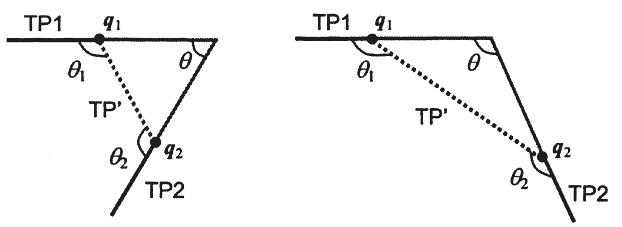

Fig. 8 Scheme 2 does not induce a sharp corner

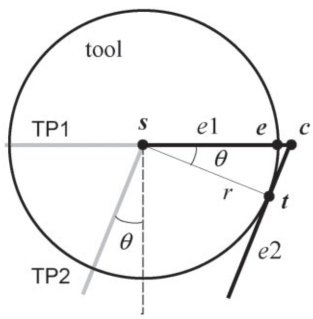

Fig. 9 Unfavourable linking result in scheme 4

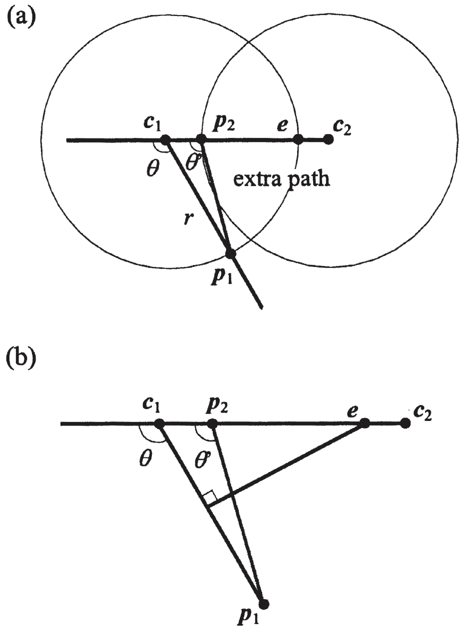

Fig. 10 Add an extra path to eliminate the inadmissible linking condition

trimmed edge $\boldsymbol{sc}$ can be expressed by

$$|\boldsymbol{sc}| = |\boldsymbol{st}| \sec\theta = r\sec\theta \geqslant r \tag{5}$$

Indeed, the cutting action does not take place along $\boldsymbol{ec}$. A remedial procedure is needed to correct this situation.

A similar situation also occurs in configuration (7). For a simple illustration, here this case is used as an example to explain the remedial procedure. The initial step is to calculate the points with a distance r to the end points on each offset edge, denoted as $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ in Fig. 10a. The portions $\boldsymbol{p}_1\boldsymbol{c}_1$ and $\boldsymbol{p}_2\boldsymbol{c}_2$ are then trimmed from the paths. The next step is to add a linking edge $\boldsymbol{p}_1\boldsymbol{p}_2$. This operation inevitably increases the angle introduced by the resultant tool paths, i.e. $\theta \rightarrow \theta'$. It is necessary to evaluate the amount of the increment to determine whether the modified tool paths are acceptable. Applying the cosine law in the triangle $\boldsymbol{p}_2\boldsymbol{p}_1\boldsymbol{c}_1$ leads to (see Fig. 10b)

$$|\boldsymbol{p}_2\boldsymbol{p}_1|^2 = |\boldsymbol{p}_2\boldsymbol{c}_1|^2 + |\boldsymbol{p}_1\boldsymbol{c}_1|^2 - 2\cos(\pi-\theta)|\boldsymbol{p}_2\boldsymbol{c}_1||\boldsymbol{p}_1\boldsymbol{c}_1| \tag{6}$$

which can be rewritten as

$$|\boldsymbol{p}_2\boldsymbol{p}_1|^2 = \left(r - \frac{r}{\sin\theta}\right)^2 + r^2 - 2\cos(\pi-\theta)\left(r - \frac{r}{\sin\theta}\right)(r) \tag{7}$$

where $|\boldsymbol{p}_2\boldsymbol{c}_1| = r - r/\sin\theta$ and $|\boldsymbol{p}_2\boldsymbol{c}_1| = r$. Hence $|\boldsymbol{p}_2\boldsymbol{p}_1|$ is expressed as

$$|\boldsymbol{p}_2\boldsymbol{p}_1| = r\sqrt{1 + (1-\csc\theta)^2 + 2\cos\theta(1-\csc\theta)} \tag{8}$$

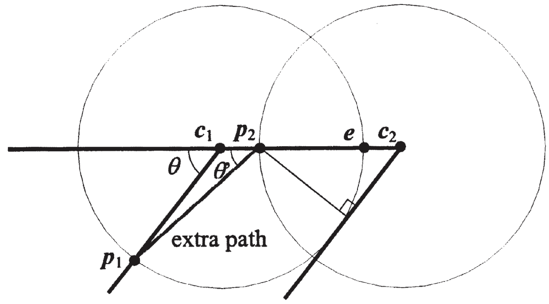

Fig. 11 Applying scheme 4 to configuration (8)

Once $|\boldsymbol{p}_2\boldsymbol{p}_1|$ has been obtained, θ' can be solved from the following trigonometric relation:

$$\frac{|\boldsymbol{p}_2\boldsymbol{p}_1|}{\sin(\pi-\theta)} = \frac{|\boldsymbol{p}_1\boldsymbol{c}_1|}{\sin\theta} \tag{9}$$

i.e.

$$\frac{|\boldsymbol{p}_2\boldsymbol{p}_1|}{\sin(\pi-\theta)} = \frac{r}{\sin\theta} \tag{10}$$

Therefore θ' is expressed as

$$\theta' = \sin^{-1}\left[\frac{\sin^2}{\sqrt{1+(1-\csc\theta)^2 + 2\cos\theta(1-\csc\theta)}}\right] \tag{11}$$

and $\Delta\theta = \theta' - \theta$ is obtained. The same formula is applicable to configuration (8), as shown in Fig. 11. In contrast, edge shortening does not occur in configuration (9). However, a check has to be made as to whether a sharp corner will occur. Figure 12 shows that this situation never happens, as both θ_1 and θ_2 are greater than θ, which is similar to scheme 2.

The tool exits discussed in this paper occur only when the tool is encountering an adjacent edge [**7**]. In this case, a circular edge (e_2) can be treated as a straight edge (e_2') tangent to the arc at the joint vertex, as shown in Fig. 13a. The exit-free offset range of e_2 is identical to that of e_2', which has been discussed in previous work [**9**]. Figures 13b and c illustrate similar situations for circular–straight and circular–circular edges with the

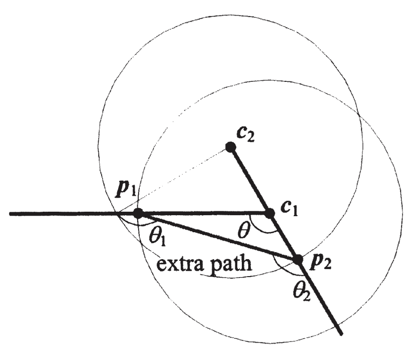

Fig. 12 Sharp corners do not arise in configuration (9)

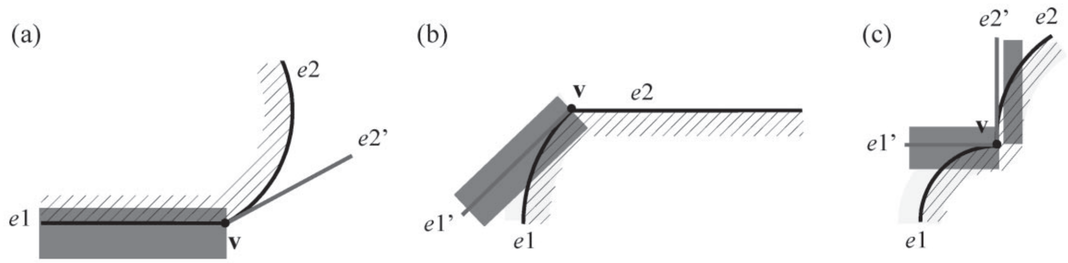

Fig. 13 Linking tool paths for circular contours

exit-free regions illustrated in different colours. Thus the proposed linking methods are applicable to circular contours.

4 IMPLEMENTATION AND TEST RESULTS

The proposed approach has been implemented in an integrated computer aided design/manufacture (CAD/CAM) system [10] as a special tool path planner for edge precision machining. The user is allowed to design a part in the system, specify machining parameters, and the exit-free tool paths are then generated in an automatic manner. Figure 14a illustrates the assumption that the test part is produced by a casting process. A typical scenario is that a layer of material needs to be removed from the part to ensure surface finish and/or dimensional specifications. Serious edge defects may form along the edges where the tool exits the part while removing the stock material. These defects can be reduced simply using geometric approaches. Firstly, the machined contours are analysed with the results

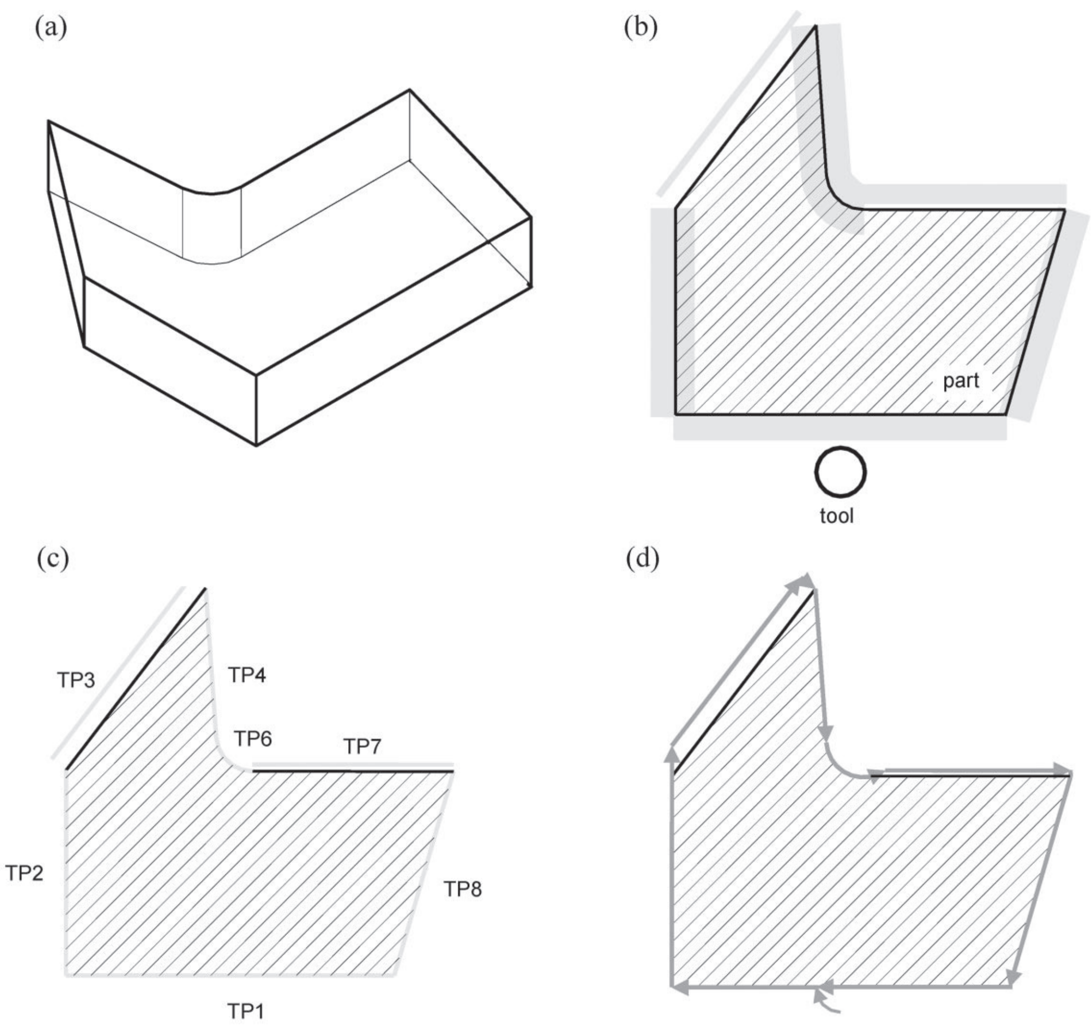

Fig. 14 Test example and the results of linking tool paths

obtained in section 2. Appropriate offset ranges are thus computed for tool exit avoidance. They are displayed in light shades along the part edges, as shown in Fig. 14b. The previously mentioned heuristics are then adopted and a unique distance is chosen to offset each part edge, resulting in the paths denoted from TP1 to TP7 in Fig. 14c. The geometric configuration of every offset pair is determined according to the procedure described in the Appendix and is classified into the list shown in Fig. 7. The corresponding scheme is then applied to link individual tool paths. The finished tool paths effectively surpass the formation of the primary edge defect. In addition, they will not cause unfavourable cutting conditions.

5 CONCLUSIONS AND DISCUSSIONS

Previous studies have shown that machining edge defects can be significantly reduced when the tool is prevented from exiting the part while removing the material or exiting only under carefully prescribed conditions. Geometric algorithms that generate exit-free tool paths have thus been developed. These algorithms may require different distances in offsetting the part edges. Linking such offset edges often results in tool motions that cause cutting conditions, including excessive tool engagements, jerks and additional tool exits. Very few studies have been concerned with this problem. To overcome this deficiency, this study proposes a computational approach to linking consecutive tool paths offset from part edges with different distances. Possible configurations of offset pairs have been identified and categorized into four groups. The offset edges in each group are connected with a special scheme consisting of three basic geometric operations. The consequent tool paths have been examined and the results have shown that unfavourable cutting conditions do not arise. The proposed approach has been implemented in an integrated CAD/CAM system as a special tool path planning agent for reducing edge defects automatically. The edge quality produced in planar milling has been substantially enhanced with application of the special tool paths. This work also provides effective solutions for similar path linking problems in a variety of occasions such as trajectory planning of a welding robot and tool path planning for contant tool engagement.

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APPENDIX

Geometric configurations of offset edges

This appendix describes the derivation of the offset edge configurations by imposing the heuristics made in section 3. Figure 15 illustrates all possible cases with the first edge (the left one) generated according to the offset type 1 range shown in Fig. 6. The angle determined by the first and the second edges can be orthogonal, convex or concave. As a result, nine combinations occur given such a first edge. The same conclusion holds for a first edge of offset type 2 and 3 ranges. Therefore the total number of edge configurations is 27. However, some of them have to be removed from the list because they never arise subject to these heuristics: (a) a zero offset value is selected for edges of the offset type 1 range and (b) the minimal offset distance is chosen for the offset type 2 and 3 ranges. For instance, it is not possible for configuration (1b) to happen as the exit-free tool path should lie outside the part along the first edge according to equation (2). Similar arguments can be used to eliminate a large number of edge configurations. Figures 15, 16 and 17 show the remaining

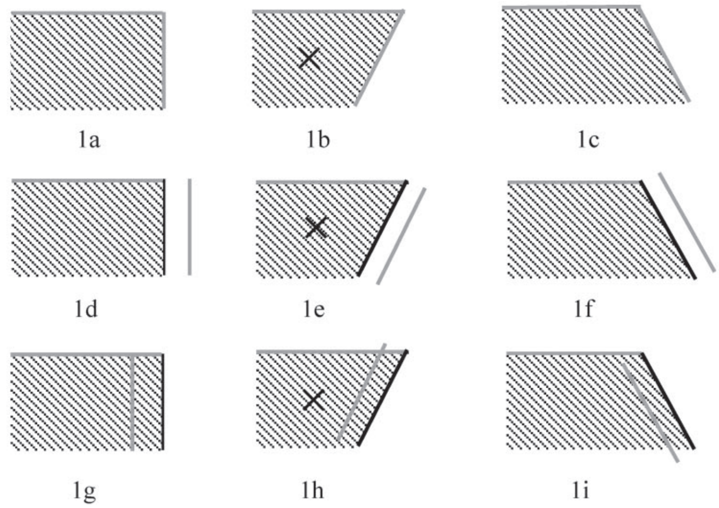

Fig. 15 Offset edge configurations for a first edge of offset type 1

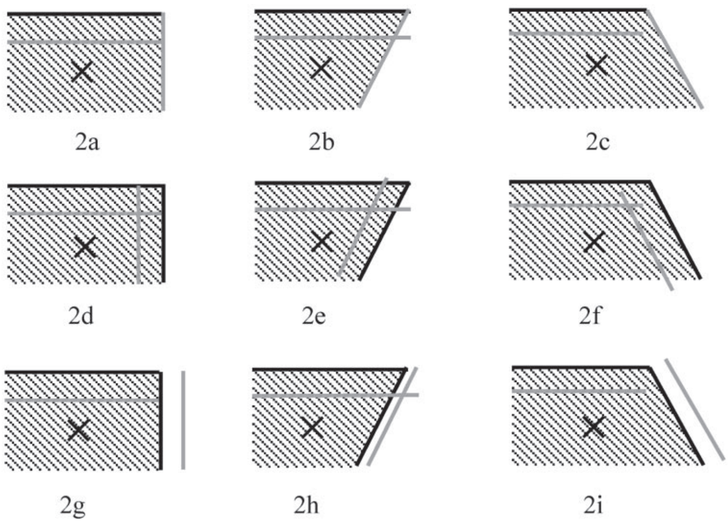

Fig. 16 Offset edge configurations for a first edge of offset type 2

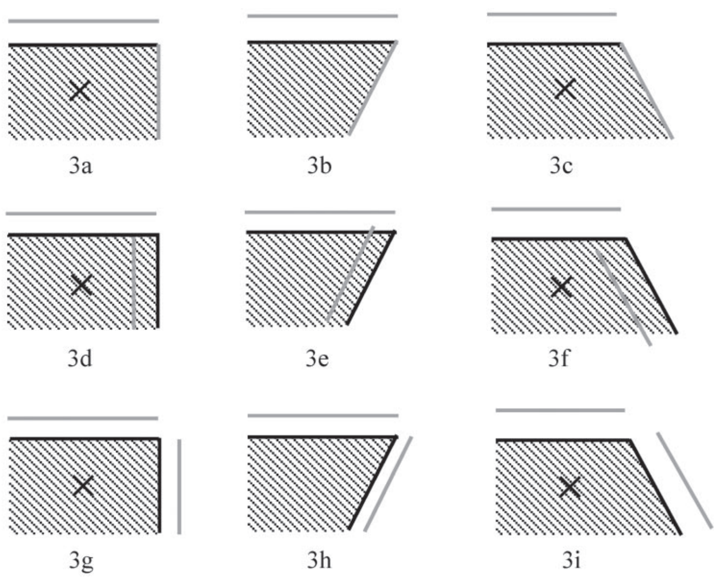

Fig. 17 Offset edge configurations for a first edge of offset type 3

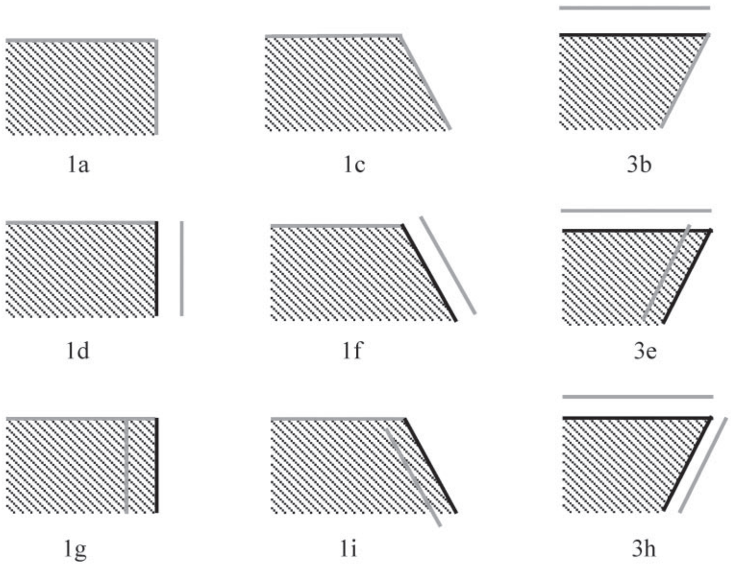

Fig. 18 Geometric configurations of two adjacent offset edges for an external contour

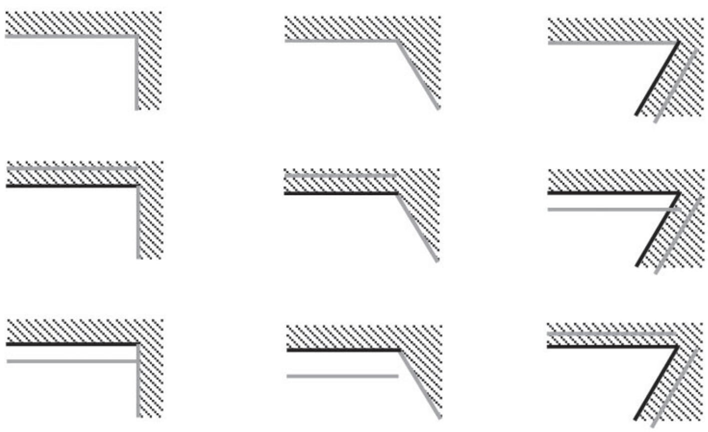

Fig. 19 Geometric configurations of two adjacent offset edges for an internal contour

cases for the first edge of the offset type 1, 2 and 3 ranges respectively. Impossible configurations are indicated by a cross sign. Totally, nine distinct configurations have to be taken into account in the tool path linking, as shown in Fig. 18.

Note that the same simplifying process can be applied to an internal contour, leaving another set of nine different configurations, shown in Fig. 19. Each configuration in the internal contour has a dual part in Fig. 19.