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Process Planning for Corner Machining based on a Looping Tool Path Strategy

Avisekh Banerjee*†

Department of Mechanical and Materials Engineering,
The University of Western Ontario, London, Ontario, Canada, N6A 5B9

Hsi-Yung Feng

Department of Mechanical Engineering,
The University of British Columbia, Vancouver,
B.C., Canada V6T 1Z4

Evgueni V. Bordatchev

Center for Automotive Materials and Manufacturing,
Industrial Materials Institute, National Research Council of Canada,
London, Ontario, Canada N6G 4X8

Abstract:

Corner is an elemental machining feature for internal pockets and involves high complexities in its planning. During machining of a Corner, there is continuous variation in radial depth of cut and frequent changes in magnitude as well as direction of the feed rate. These result in inconsistent machining leading to machine tool jerk, excessive cutting force and poor surface finish. In this paper, a process planning approach has been proposed for optimal Corner machining combining, tool path generation and machining parameter selection. At first a Looping tool path strategy has been implemented to progressively remove material in multiple loops to maintain radial depth under permissible limits. The tool path consists of G^1 continuous biarc and arc spline segments which allow a constant feed rate to be held over the entire tool path. The geometry of Corner and cutting tool as well as kinematics of machine tool structure is considered while calculating the allowable constant feed rate. In the next step, machining time is minimized by iteratively adjusting the feed per tooth value under cutting force

* corresponding author, e-mail: banerjeea@lifepredictiontech.com; Tel: 613-744-7574; Fax: 613-744-5278

† now with Life Prediction Technology Inc., Ottawa, Ontario, Canada, K1J 9J1

constraints. The constraint ensures that the tool deflection is always under a tolerance limit. The resulting tool path for different test cases indicates the ability of the tool path generation strategy to minimize the number of loops. The cutting force calculations for the test cases suggest that the proposed process planning can potentially improve productivity of Corner machining.

Keywords: Corner Machining; Process Planning; Looping Tool Path; Cutting Force;

1. Introduction

Corner machining is primarily a finishing operation and unavoidable while machining internal pockets with a desired finished radius. The generated machined surface is critical for part acceptability especially for die-mold and mating components. The geometry of a typical Corner is shown in Figure 1a. The material to be removed during Corner machining (m_C) shown by the shaded region, is defined by the material profile boundary (R_R) generated by previous material removal processes, the desired finished Corner radius (R_F) and the pocket boundary. It can be observed that the radial depth of cut (d_r) is continuously varying over the entire m_C and shown in Figure 1b. Even if a constant material d_r could be achieved by removing material (d_m) with a circular tool path segment having a radius R as shown in Figure 1a, but d_r while removing the remaining material cannot be maintained constant. In order to generate the finished radius R_F during Corner machining with a single tool with radius r , R_F should be greater or equal to r . Hence tool path generation for machining a Corner feature involves significant geometric considerations.

The machining parameters involved during Corner machining are shown in Figure 1b. These include the radial depth of cut (d_r), feed rate (V), height of the Corner (h) and number of axial passes (n_a). The tool and machine tool rigidity and kinematic properties would determine the value of the stable axial depth limit (a_{lim}) that can be used without resulting in chatter. The number of axial passes required to completely machine the height h with a_{lim} in each pass would determine the value of n_a .

During Corner machining, the instantaneous d_r keeps changing which results in large variations of cutting force [1-3]. This may lead to excessive tool deflection and

unacceptable machined profile and even tool breakage [4-9]. Thus a maximum radial depth of cut ($d_r^{\max}$) should be permitted to guarantee the generated cutting force would result in machined accuracy within a prescribed tolerance. The machining accuracy constraint would limit the value of $d_r^{\max}$ and require a tool path strategy to progressively remove the material with multiple tool passes.

Moreover, geometry of the Corner does not allow the tool to move at constant feed rate and frequent changes of tool path direction are also required. Tool needs to slow down or even stop during the machining depending on the geometry of tool path [10]. The instantaneous changes in feed rate along the tool path are also not possible due to the acceleration/deceleration profiles of practical machine tools [11] and results in increased machining time and surface errors.

Both geometric as well as machining considerations are involved in developing a integrated process planning strategy for Corner machining. The integrated process planning can be divided into three major tasks [12], namely, Tool Selection, Tool Path Generation and Machining Parameter Selection. The finished radius of Corner, R_F and tool radius are the important factors for Tool Selection [13]. For Tool Path Generation, tool path geometry, machine tool kinematics and machining parameters are considered. Choy *et al.* [14-16] proposed looping tool path for Corner in pocket machining based entirely on the geometry. To reduce the cutting force encountered during Corner machining, single loop and double loop strategies were proposed. However the number of cutting passes was not optimized based on physical constraints. Moreover the cut pattern had geometric discontinuities which led to decrease in the feed rate and possibility of sudden rise in cutting force. On the other hand, Erkorkmaz and Altintas [17, 18]

presented cut patterns based on quintic spline to provide smooth and consistent feed rate. Bieterman and Sandstrom [19] described a method to generate a spline tool path in the pocket machining by eliminating internal tight-radius Corners. However reliable higher order interpolations required to perform spline interpolation are not commonly available in commercial CNC machines. In an approach to avoid the sudden rise of cutting force in the Corner, feed rate had been adjusted [20-22] during machining. Again to handle instantaneous variations in the feed rates would require sophisticated CNC machine controllers with fast response time. Concurrently the frequent changes of feed rate in the tool path would also deteriorate the finished surface quality [7] and increase the machining time.

The varying cutting conditions and directions during Corner machining also make the optimal Machining Parameter Selection difficult. The cutting force [2, 3, 22], machining accuracy [4-9] and Material Removal Rate (MRR) [24], are considered as reliable indicators of consistent and productive machining. Under an integrated process planning approach [12], the process planning tasks have to be individually represented as a well-defined optimization problem. The tasks have to be simultaneously optimized under physical constraints to achieve a globally optimal plan for Corner machining. Since Corner machining is considered as a finishing or semi-finishing operation, representing the physical constraint with cutting force based tool deflection will be the most appropriate.

In this paper, the individual planning tasks for Corner machining have been considered in details and integrated to generate optimal process plans rather than considering them as individual problems. The goal is to maximize productivity of the

end-milling operation under prescribed constraints by enabling consistent machining and maintaining constant feed rate. In particular, a novel multiple Looping tool path [24] is implemented to enable consistent and smooth machining and simulated with instantaneous cutting force calculation. The rest of the paper is organized in the following manner. Section 2 provides the considerations for process planning for Corner machining including the planning tasks and constraints. In Section 3, the implemented Looping tool path is described in details along with its procedure and results of test cases. Section 4 discusses the process optimization of Corner machining based cutting force calculations along with the implementation details and result of test cases. Finally the conclusions from the obtained results are summarized in section 5 to validate the process improvement capabilities of the proposed process planning approach.

2. Considerations for Process Planning

2.1. Tool Selection

The main consideration during Tool Selection for Corner machining is accessibility of the tool with radius r to generate a finished radius R_F which imposes geometrical constraint for tool selection. Moreover there is also a limitation on the tool path radius which can be used on a particular machine tool based on its kinematics. This imposes further restrictions on the tool radius suitable for Corner machining especially for generating R_F . The kinematics of the machine tool like the maximum acceleration (A), jerk (J) and elemental time (ΔT) parameters dictates the value of the limiting feed rate

($V_{\lim}^{\min}$) that can be maintained over a minimum curvature radius R_C and given by the following equation [10],

$$R_c = \max\left(\frac{V_{\lim}^{\min 2}}{A}, \frac{V_{\lim}^{\min 2}}{J \times \Delta T}\right) \quad (1)$$

Hence the constraint $R_F \geq r + R_c$ has to be satisfied, otherwise a smaller tool radius r needs to be selected. The selection of maximum tool radius satisfying the above condition will result in the minimum machining time.

2.2. Tool Path Generation

The Tool Path Generation for Corner machining is a complicated issue evident from the large number of published work. During Corner machining, if tool is driven in a linear path radial depth (d_r) changes continuously which lead to high variation in process outputs. Hence circular tool paths are often used to obtain consistent [3, 14-16] or even constant d_r which can be limited within a maximum value of $d_r^{\max}$. This may require the material to be removed in multiple tool passes [7] consisting of linear and circular segments. For multiple passes, there will be frequent changes in cutting direction which necessitates slowing down the tool or even stopping it. This will lead to higher machining time [6] and deterioration of machined surface quality due intermittent feed rate variation [7]. Hence, a G^1 continuous tool path consisting of composite linear and circular segments can significantly reduce fluctuations in cutting direction as well as feed rate. This can be enabled with biarc and arc spline which are G^1 continuous circular-circular segments and circular-linear segments respectively, shown in Figure 2a and 2b, respectively. The biarcs and arc splines are defined with two end positions and tangent

information as well as the G^1 continuity maintained at their intersection points. In order to uniquely define the intersection point, an additional constraint of minimizing the absolute difference between two curvatures is applied.

2.3. Machining Parameter Selection

The instantaneous radial depth changes during Corner machining. This leads to large variation in cutting force as well as generated surface profile due to tool deflection. With a multi-looped tool path for progressive material removal, the primary objective of planning task of Machining Parameter Selection is to select feed per tooth value such that machining time is minimized under a cutting force constraint. The limiting cutting force (F_{lim}) will ensure that tool deflection is within prescribed tolerance (τ). Based on an initial feed value selected from a machining handbook [25], the instantaneous cutting force (F_{inst}) can be calculated for the Looping tool path with a mechanistic model [26]. The feed per tooth is iteratively adjusted such that maximum F_{inst} is just under F_{lim} which ensures the resulting tool deflection is always smaller than τ . The cutting force modeling along circular tool path would require a modified feed per tooth calculation based on the distance between two consecutive epitrochoidal tooth trajectories.

2.4. Limiting Feed Rate at Curvature Discontinuities

In order to avoid tool stoppages during Corner machining, G^1 discontinuities have to be avoided in the tool path geometry. This can be achieved by using trajectories with higher order curves. However while machining along such curves, the machine tool controller may not provide reliable interpolation. One of the most effective ways of

maintaining a constant feed rate along the entire tool path machined in commercial CNC is to use G^1 continuous biarc and arc spline, shown in Figure 2.

However the tool path radius and curvature discontinuities at intersections of biarc and arc spline limit the permissible feed rate at these points. This limiting feed rate (V_{lim}) for each type of segments and their intersections can be calculated based on radii (R_1 and R_2) of the two circular segments and machine tool kinematics like maximum acceleration (a_{max}), jerk (J), elemental time (ΔT) and given as below [10],

- Along an arc segment: $V_{lim}^{arc} = \sqrt{a_{max} \times R_1}$ (2a)

- At an arc-arc intersection: $V_{lim}^{arc-arc} = \sqrt{\frac{R_1 \times R_2}{|R_1 - R_2|} \times (J \cdot \Delta T)}$ (2b)

- Along a line segment: $V_{lim}^{line} = V_{max}$ (2c)

- At a arc-line intersection: $V_{lim}^{arc-line} = \sqrt{R_1 \times (J \cdot \Delta T)}$ (2d)

The value of the maximum feed rate, V_{max} depends on the capability of the machine tool and its motion controllers. The V_{lim} along circular segments and intersections is lower than V_{max} as observed from Equation 2. The minimum V_{lim} for all the circular segments and the intersections, say V_{lim}^{min} , can be maintained throughout the tool path during Corner machining and enable consistent machining. Hence both the geometry of the tool path as well as the machine tool kinematics plays an important role in process planning for Corner machining.

2.5. Cutting Force and Tool Deflection Model

Corner machining is a semi-finishing or finishing operation with primary focus to achieve desired machined surface quality. Hence, the maximum tool deflection ($\delta_{\max}$) should always be maintained lower than a prescribed surface quality tolerance τ . If $\delta_{\max}$ is greater than τ , the feed per tooth value should be reduced such that generated cutting force and subsequently the tool deflection are lower. For implementing surface quality constraint based process optimization, cutting force and tool deflection models are required.

In this paper, the instantaneous cutting force for Corner machining is calculated based on a pre-calibrated mechanistic force model [26]. The model is improved to accommodate variation in radial depths and chip thickness variation for circular cuts. The basic governing equations can be represented as follows:

$$\begin{aligned}
 F_{X_{\text{inst}}} &= \sum_{\theta=\theta_{\text{entry}}}^{\theta=\theta_{\text{exit}}} \sum_{dz=0}^{dz=d_s} -K_T \cdot dz \cdot \left[\{t_c(\theta)\}^{m_T} \cdot \cos(\theta) - K_R \cdot dz \cdot \{t_c(\theta)\}^{m_R} \cdot \sin(\theta) \right] \\
 F_{Y_{\text{inst}}} &= \sum_{\theta=\theta_{\text{entry}}}^{\theta=\theta_{\text{exit}}} \sum_{dz=0}^{dz=d_s} K_T \cdot dz \cdot \left[\{t_c(\theta)\}^{m_T} \cdot \sin(\theta) - K_R \cdot dz \cdot \{t_c(\theta)\}^{m_R} \cdot \cos(\theta) \right] \\
 F_{\text{inst}} &= \sqrt{F_{X_{\text{inst}}}^2 + F_{Y_{\text{inst}}}^2}
 \end{aligned} \tag{3}$$

where $F_{X_{\text{inst}}}$ and $F_{Y_{\text{inst}}}$ are components of F_{inst} in X and Y direction, d_z is elemental height of the unit cutting disk, t_c is instantaneous undeformed chip thickness, θ is angular position of the tool, θ_{entry} and θ_{exit} are angles of entry and exit and K_T , K_R , m_T and m_R are empirical coefficients in tangential and radial directions [26].

A static tool deflection model [4 and 26] has been implemented to calculate the maximum tool deflection ($\delta_{\max}$) along Y direction of tool during Corner machining. The

model is based on a cantilever beam theory and tool deflection along Y direction, δ_Y is given by,

$$\delta_Y(z_i) = \frac{F_{Y_{\max}}(\theta_i)}{6 \cdot E \cdot I_Y} \cdot \left[\langle C_Y(\theta_i) - z_i \rangle^3 - (L - z_i)^3 + 3(L - z_i)^2 (L - C_Y(\theta_i)) \right] \quad (4)$$

where P_Y is the intensity of cutting force in Y direction distributed along axial immersion of the tool; C_Y is the distance of the centre of the equivalent moment; E is Young's Modulus for tool material, I is moment of inertia of tool given by $I_Y = d^4 / 48$, d being tool diameter; $\langle \rangle$ is a mathematical operator which denotes that if value inside it is negative, the value is set as zero; L is free length of tool; z is surface generation point; θ is the angular orientation of tool and β is the helix angle.

3. Looping Tool Path

The major requirements of an efficient tool path for Corner machining are consistent radial depth of cut, d_r less than a prescribed maximum $d_r^{\max}$ and minimization of feed rate fluctuation. These would ensure more consistent and smooth material removal and avoid the sudden increase in the cutting force during machining the Corner. The feed rate fluctuations occurring due to tool slow down and stoppage deteriorate the machined quality and increase machining time. The ability to maintain a constant feed rate along the tool path will minimize and even avoid feed rate fluctuations. For this purpose, geometry, machine tool characteristics and process parameters needs to be simultaneously considered for a holistic process planning approach.

The Looping tool path consisting of G^1 continuous composite circular and linear segments represented with biarc and arc spline have been developed [24] with an aim to achieve consistent machining by progressively removing materials in multiple loops. In this strategy, d_r for circular segments varies consistently during machining in individual loop and is kept under $d_r^{\max}$. The linear segments are used to position the tool such that d_r of the subsequent circular segment is close to $d_r^{\max}$ to maximize the machining capabilities and increase productivity. The G^1 continuity allows a minimum limiting feed rate, $V_{\lim}^{\min}$ to be maintained along the entire tool path. The geometry of the linear and circular tool path segments are determined [24] based on geometry of cut, tool radius, process and machine tool capabilities, and minimum radius of curvature required to move the tool with $V_{\lim}^{\min}$.

3.1. Different Loops

A typical Looping tool path for Corner machining can have three different types of loops depending on the geometry of tool and material to be removed. The different loops are, initial (T_j^i), intermediate (T_j^{int}) and final (T_j^f) loops, as shown in Figures 3, 4 and 5, respectively.

- The initial loop (T_j^i) machines the roughed annular quadrant ($A_R-B_R-B_{\text{int}}-A_{\text{int}}$) with width d_m and shown by the dotted region in Figure 3. Radial depth of cut for this loop is d_m to avoid any overcut and its maximum value is $d_r^{\max}$. This loop starts with a circular segment ($T_1^i - T_2^i$). The segment has a radius of R_i and generates the first intermediate roughed profile ($A_{\text{int}}-B_{\text{int}}$) with radius, $R_{R-\text{int}}$. The return path ($T_2^i - T_3^i -$

$T_4^i - T_1^i$) consists of G^1 continuous arc splines with the radius and included angle of two circular segments being the same. The values are calculated based on the desired constant feed rate to be maintained and relevant geometric information.

- A typical intermediate loop (T_j^{int}) removes the material (shown in dotted) till the profile $A'_{int} - B'_{int}$ with radius $R'_F \geq r_F + d_r^{max}$ is generated as shown in Figure 4. The above condition ensures that material left in the final loop is less than d_r^{max} . Depending on the geometry and value of d_r^{max} , the number of intermediate loops required and their corresponding tool path radius (R_j^{int}) can be determined. The final intermediate loop will be generated such that the maximum radial depth in the final pass is d_r^{max} or less. For the sake of simplicity, only one intermediate loop is shown here. The loop starts with a linear segment ($T_1^{int} - T_2^{int}$) of length L^{int} till the point where the maximum radial depth (d_r^{int}) of the subsequent circular segment ($T_2^{int} - T_3^{int}$) is lower than d_r^{max} . At the end of the circular segment, the tool returns back to the starting point of the next loop. The return path ($T_3^{int} - T_4^{int} - T_5^{int} - T_2^{int}$) is an arc spline similar to that of the initial loop.
- The final loop (T_j^f) machines the remaining material (shown in dotted) to generate the finished pocket boundary ($A_F - B_F$) with radius R_F , and shown in Figure 5. Like intermediate loop, the tool starts with a linear ($T_1^f - T_2^f$) segment of length L^f and then a circular ($T_2^f - T_3^f$) segment. The radial depth for this loop is always maintained under d_r^{max} due to the material removed by earlier loops. On reaching the end of the

circular segment ($T_2^f - T_3^f$), the tool moves in a linear ($T_3^f - T_4^f$) path to finish the pocket boundary.

3.2. Procedure

The details of the Looping tool path [24] geometry can be calculated based on the material removed by corner machining, tool radius, machine tool kinematics and practical machining heuristics. The steps involved in the construction of Looping tool path is given below and shown in Figure 6. At first, tool is selected to enable the machining of the finished radius R_F by maintaining the maximum possible feed rate. The geometries of the initial, intermediate and final loops are calculated to progressively remove material. The calculations are based on the geometry of segments, machine tool capabilities and a constant feed rate that can be maintained along the entire tool path, such that tool path length is also minimized.

4. Process Optimization and Result

The optimization of Corner machining is represented as simultaneous optimization of Tool Selection, Tool Path Generation and Machining Parameter Selection under given physical constraints. At first the Looping tool path [24] is implemented for different tool and Corner geometries to study its capability to minimize tool path length or number of loops by maximizing the utilization of the constraint of the radial depth being under a certain maximum value. In the next step a mechanistic cutting force model [26] has been used to calculate the instantaneous cutting force profile along the looping tool path.

Based on the limiting cutting force constraint calculated using a static tool deflection model, optimal feed is calculated iteratively.

4.1. Number of Loops

The number of loops required to machine a Corner directly indicates the productivity of the process. Hence it should be optimized with respect to given geometry of tool and Corner as well as the process and machine tool capabilities. For this purpose, different cases of Corner and tool geometries have been considered and shown in Table 1. The Looping tool path for Corner machining, represented in terms of biarcs and arc spline has been generated for each of the cases. The given geometric parameters are tool radius (r), initial roughed radius (R_R) and finished radius (R_F). The machining parameters and machine tool characteristics given in Table 2 are used to calculate the minimum curvature radius (R_c) required to maintain a constant feed rate of V_{lim}^{min} . The machining data and the dynamic properties of machine tool structure are selected from handbook [25] and previous work [10, 11]. The geometric cases are selected such that multiple tool passes are required with at least one intermediate loop as shown in Table 1.

The Looping tool path for the different geometric cases are shown in Figure 7. It is observed in Figure 7a and 7b that the number of loops required for test Case 1 is higher than test Case 2. The initial roughed radius, R_R for Case 1 is higher for the same r , suggesting higher material is to be removed which leads to higher number of loops. As the amount of material to be removed are similar in Cases 2 and 3, in spite of having different R_R and R_F , the number of loops are same, as shown in Figure 7b and 7c. When Figure 7b and 7d are compared, the number of loops is the same although r changes for

the same R_R and R_F . This implies that the Looping path tries to minimize number of loops by maximum utilization of the constraint $d_r \leq d_r^{\max}$.

4.2. Mechanistic Cutting Force Model and Constraint

The maximum tool deflection ($\delta_{\max}$) should always be maintained lower than the prescribed tolerance (τ) to guarantee the generation of acceptable Corners. If $\delta_{\max}$ is greater than τ , value of feed per tooth has to be iteratively changed such that generated cutting force is lower and vice versa. Based on the cutting force coefficients in Table 1, cutting force simulation (Equation 3) and tool deflection model (Equation 4), the limiting instantaneous force ($F_{\lim}$) to enable $\delta_{\max}$ to be less than $\tau=0.005\text{mm}$ was calculated as 796.3 N.

Corner geometries corresponding to Case 2 and 1 (Table 1) have been considered for feed optimization based on $F_{\lim}$. Apart from the initial loop, radial depth of cut and entry angle constantly changes. In the first step F_{inst} is calculated based on the initial feed of 0.0381 mm/tooth [25] for a HSS tool and mild steel workpiece combination. In the second step, the feed optimization is done by iterative selection of feed per tooth such that the calculated F_{inst} is always within $\pm 5\%$ limit of $F_{\lim}$. Since the machining data obtained from handbooks [25] tends to be conservative and does not consider machine tool capabilities, it is not difficult to obtain higher optimal feed. However, the higher feed also increases the return radii of the looping path and actually increases the total tool path. But the increase in total tool path length is adequately compensated by the increase in the feed rate leading to overall reduction in machining time.

For Case 2, three loops are required to machine the Corner which can be observed in Figure 8a. In Figure 8b the value of θ_{entry} remains constant for the initial loop and becomes 180° for the return path which signifies no engagement. The two subsequent variations from 180° imply the cutting in the intermediate and final loops with reducing d_r . The Figure 8c shows the comparison of the calculated instantaneous force, F_{inst} profiles with initial and optimal feed. The initial loop has consistent force profile due to constant d_r . For the subsequent loops, d_r and F_{inst} initially increases till a maximum (d_r^{max}) near the center of the circular tool path and then decreases. The maximum F_{inst} , $F_{\text{inst}}^{\text{max}}$ is 612.3 N calculated with initial feed of 0.0381 mm/tooth. The result of the optimal feed selection leads to a feed of 0.0538 mm/tooth and corresponding $F_{\text{inst}}^{\text{max}}$ being 794.6 N occurring in the initial loop. The tool path length increases by 9 mm, suggesting overall increase of 19.2 % in productivity.

For Case 1, the plot of the tool path, (θ_{entry}) and F_{inst} is shown in Figure 9. There are four loops which lead to higher tool path length. Four distinct profiles are also observed in the calculated F_{inst} with reducing magnitude corresponding to progressively lower material remaining to be removed in each loop. In this case, the optimized feed is again 0.0515 mm/tooth as the maximum F_{inst} occurs in the initial loop. The tool path length increases by 4.1 mm to accommodate the higher feed rate, but the overall increase of productivity is 27.6 %.

The cutting force based feed per tooth optimization for different geometric cases of Corner given in Table 1 was conducted. The summary of cutting force based result is presented in Table 3. The machining time is calculated based on initial and optimal tool

path length and feed per tooth. The optimal feed per tooth and its corresponding tool path length consistently leads to lower machining time. The table suggests that the proposed integrated process planning with Looping tool path and feed per tooth optimization has the potential of improving productivity of Corner machining. It does not depend only on tool path length but also depends on the simultaneous consideration of both tool path length as well as machining parameters like feed per tooth. Thus pure geometric approach to maximize productivity of Corner machining is inadequate. A smoother machining and consistent feed rate strategy also enables the maximum utilization of the machine tool capabilities and physical resources.

5. Conclusions

In this paper, an integrated process planning framework has been presented to generate optimal plans for Corner machining with minimum machining time under physical constraints. For this purpose Tool Selection, Tool Path Generation and Machining Parameter Selection has been considered simultaneously. To achieve consistent machining under prescribed geometric and machining constraint, a Looping tool path strategy has been implemented. The strategy results in progressive material removal in number of loops with the radial depth controlled under certain limit. The tool path consists of biarc and arc spline segments which preserves the G^1 continuity and enables a constant feed rate to be maintained over the entire tool path. Tool path geometry is combined with the machine tool kinematics to determine limiting tool path radius and feed rate. The cutting force calculation along the tool path with mechanistic

model provides optimal selection of feed per tooth to maximize process utilization under given constraints by minimizing the machining time.

The calculation of the Looping tool path for different test geometries indicates its ability to reduce the number of loops by maximizing the constraint $d_r \leq d_r^{\max}$. This directly translates to lower path length and machining time. In the next step, a cutting force constraint derived from a static tool deflection model has been applied to minimize the machining time by optimally selecting the feed. The instantaneous cutting force simulation shows smooth and consistent cutting forces during corner machining as well as potential time saving around 27 %. This occurs in spite of the increase in the tool path length due to increase in radius of the return path in the initial and intermediate loops which increases to accommodate the higher optimal feed rates. Hence the result suggests that a purely geometric approach for process planning of Corner machining may lead to sub-optimal plans, and the proposed integrated process planning approach is more appropriate for planning similar or more complex machining features.

In this work, the limiting feed rate formulations for curvature discontinuities in the implemented tool path is based on rectangular shaped acceleration/deceleration profile, which is not practical. Inclusion of practical profiles in the tool path planning will improve the feed rate calculations. The current research has been done for Corner machining with simple geometry, however the proposed process planning strategy can be extended to complex shaped Corner in the future study. Different optimal feed rates can be determined for different loops to further reduce machining time.

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Table 1: Number of loops for different tool and Corner geometries calculated
with Looping tool path strategy

No.	r	R_R	R_F	Initial Loop	Intermediate Loop(s)	Final Loop
1	6.0	22.0	12.0	1	2	1
2	6.0	17.0	12.0	1	1	1
3	6.0	22.0	14.0	1	1	1
4	5.0	18.0	12.0	1	1	1

Table 2: Process parameters for cutting force calculations in Corner machining

Material	
Workpiece	: SAE 1018
Tool	: HSS
Tool Geometry	
Diameter	: 12 mm
Helix Angle	: 35°
No. of Tooth	: 4
Machining Parameters [25]	
Feed	: 0.0381 mm/tooth
Speed	: 26.0 m/min
Radial Depth	: $d/4$ (maximum)
Axial Depth	: $d/2$
Machine Tool Characteristics [10, 11]	
Max. Acceleration	: 2 m/s^2
ΔT	: 0.177 s
Jerk $\times\Delta T$	: 5 m/s^2
Cutting Force Coefficients [26]	
K_R	: 1043 N/mm^2
K_T	: 1756 N/mm^2
m_R	: 0.837
m_T	: 0.840

Table 3: Summary of optimization result of process planning for Corner geometries

Case	r (mm)	R_R (mm)	R_F (mm)	Feed per tooth (mm/tooth)		Tool path length (mm)		Potential saving in Time (%)
				Initial	Optimal	Initial	Optimal	
1	6	22	12	0.0381	0.0538	185.4	189.5	27.6
2	6	17	12	0.0381	0.0515	97.1	106.1	19.2
3	6	22	14	0.0381	0.0542	144.9	150.0	27.2
4	5	18	12	0.0318	0.0497	107.1	121.2	27.6

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Figure 2: Typical geometric representation and feed rate limitations of (a) biarc and (b) arc spline

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Figure 8: Comparison of initial and optimal feed per tooth for Corner machining-case 2,
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