Title:
Five-Axis Tool Positioning of a Toroidal End Mill Tool Near Common Edge Between Two Intersecting Surfaces

Authors:
Sandeep Kumar Sharma, sksharma@thapar.edu, Thapar Institute of Engineering and Technology, India
Ravinder Kumar Duvedi, rduvedi@thapar.edu, Thapar Institute of Engineering and Technology, India
Sanjeev Bedi, sbedi@uwaterloo.ca, University of Waterloo, Waterloo, ON, Canada
Stephen Mann, smann@uwaterloo.ca, University of Waterloo, Waterloo, ON, Canada

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Introduction:
5-axis machining offers potential benefit of achieving higher machining efficiencies particularly in machining complex surfaces as seen predominantly in forming dies, aerodynamic surfaces and turbine blades etc. Such complex engineering components invariably have edges formed by intersection of surfaces and machining such zones often is a challenge. Generally, ball end and flat end milling cutters are employed for achieving maximum material removal rate in such difficult to access zones, primarily because of ease of accessibility and relatively simpler computational effort in terms of tool positioning [2]. But these tools have inherent limitations in terms of tool life, material removal rate, quality of machined surface and total machining time [1]. The multipoint tool positioning using toroidal end mill ensures the tangency of cutter surface on at least two points on the target surface/s resulting in improved material removal rate, better quality of machined surface along with superior tool life [2], [4-6] as compared to ball and the flat end milling tools. Use of a toroidal tool becomes increasingly challenging when dealing with tensor product surfaces rather than faceted approximation to avoid any compromise with quality of machined surface [3].

In the present work, a novel approach for determining the multipoint five-axis tool positioning of generalized toroidal cutter for gouge-free machining in the region of the common edge of two tensor product surfaces is developed. The proposed drop and spin method (DSM) employs a toroidal tool with offset radius $\boldsymbol{R_o}$ and insert radius $\boldsymbol{R_i}$. The toroidal geometry is created by sweeping a circle of radius $\boldsymbol{R_i}$, also called as *"pseudo insert circle",* about the tool axis $\boldsymbol{\hat{t}}$. The key deliverable of the DSM is a pair of gouge free contact points, one on each of the intersecting surfaces.

To finish machine the common edge region between surfaces $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$, a sequence of toroidal tool positions along the common edge are computed. Tool path is generated by implementing the DSM procedure along the reference lines which are $\boldsymbol{f_{step}}$ apart. To locate the tool footprint points ($\boldsymbol{T}$) on these reference lines, equi-spaced points with a separation of $\boldsymbol{x_{step}}$ are considered (shown as dots on reference lines in Fig. 1). Our algorithm provides a zone of tool drop footprint locations along each reference line. The tool must be dropped within this unique zone to achieve simultaneous tangency with the two surfaces and effectively finish machine the common edge region. The proposed method has been successfully implemented for computing tool positions for five-axis machining over the concave and convex shaped curved edge formed by two sets of intersecting surfaces.

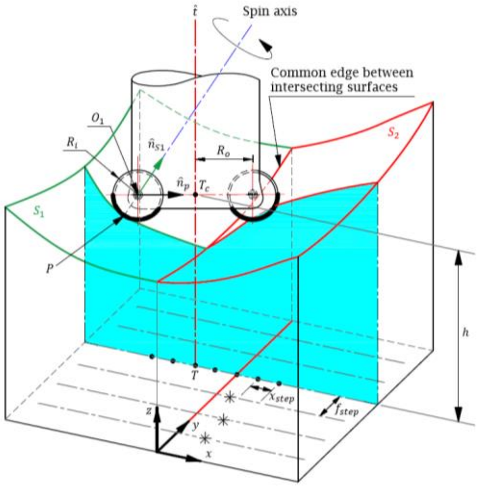
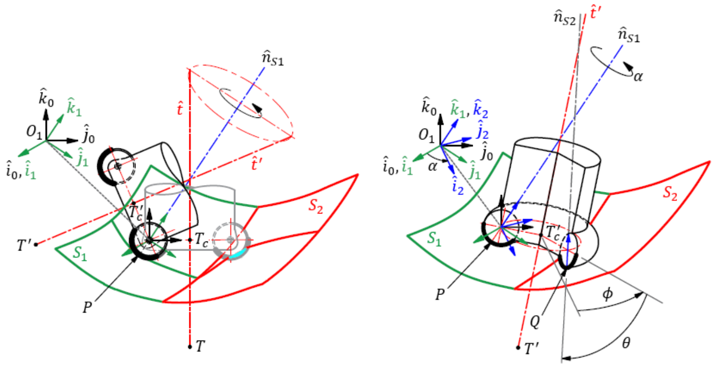


Fig. 1: The geomeric definition of a toroidal end mill tool and the definition of the toolpath footprint points determined to implement DSM tool positioning.

<u>Concept of drop and spin method:</u>
DSM essentially consists of following two steps:

1. The toroidal tool is dropped vertically along its axis ($\hat{\boldsymbol{t}}$), on one of the intersecting surfaces (Say $\boldsymbol{S_1}$) and first point gouge free contact point ($\boldsymbol{P} = \boldsymbol{S_1}(\boldsymbol{u_1}, \boldsymbol{v_1})$) is determined. The dropped tool may or may not gouge with the second surface $\boldsymbol{S_2}$ depending on the location of tool-drop footfoot
2. print $\boldsymbol{T}$.
3. The dropped tool is rotated about the surface normal ($\hat{\boldsymbol{n}}_{\boldsymbol{S1}}$), called the "*spin-axis*", to find a second gouge free contact point $\boldsymbol{Q}$ on second surface, while maintaining the contact between the tool and surface $\boldsymbol{S_1}$ at $\boldsymbol{P}$. To accomplish the tool Spin, the surface normal $\hat{\boldsymbol{n}}_{\boldsymbol{S1}}$ is considered as the "*spin-axis*". While the tool is rotated about spin-axis ($\hat{\boldsymbol{n}}_{\boldsymbol{S1}}$), tool axis ($\hat{\boldsymbol{t}}$) generates a cone as shown in Fig. 2(a). Each generatrix of this cone is a possible tool orientation. One of these tool orientations may result in simultaneous tangency between toroidal tool and intersecting surfaces.



(a) (b)

Fig. 2: Definition of geometric parameters used in DSM method: (a) Concept of rotating toroidal tool about spin-axis $\hat{\boldsymbol{n}}_{\boldsymbol{S1}}$ and (b) Determining the spin angle $\boldsymbol{\alpha}$ that enables a second point of contact $\boldsymbol{Q}$ of toroidal tool on surface $\boldsymbol{S_2}$ while tool also retains its tangency to $\boldsymbol{S_1}$ at $\boldsymbol{P}$.

Identification of Feasible spin zone:

Another important outcome of DSM is to identify the feasible tool drop footprint zone for which the rotated tool will be able to find gouge free tangency with two surfaces across the common edge. In a limiting case of tool-drop location (***T***) the dropped tool may find gouge free tangency (at points ***P*** and ***Q***) simultaneously with both the intersecting surfaces as shown in Fig.3(a). In this case there is no scope for the tool to spin, since tool is already touching both the surfaces tangentially.

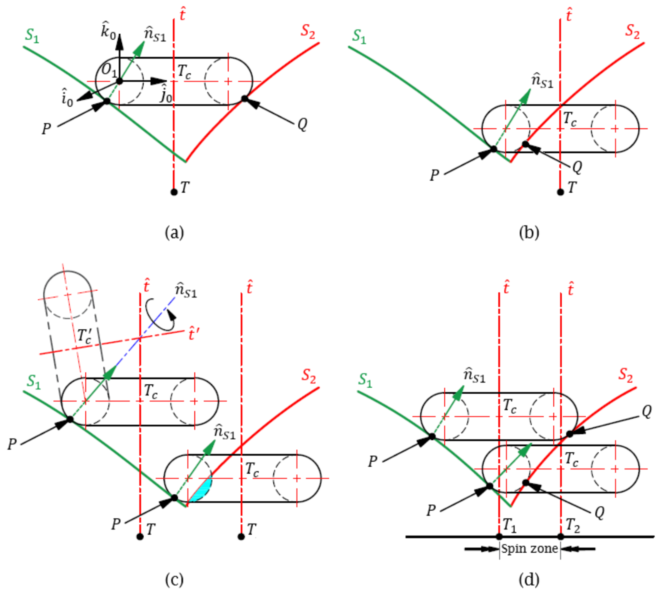


Fig. 3: Determining "*Spin Zone*" for a given pair of intersecting surfaces: (a) Dropped tool is tangent to both the surfaces, (b) Dropped tool has pseudo insert circle snugly fit between intersecting surfaces, (c) Infeasible footprint locations for DSM method and (d) Definition of limiting toolpath footprint locations for the spin-zone.

On the other extreme, there can be a footprint location (***T***) where the dropped tool may be simultaneously tangent with both the intersecting surfaces, while the two points of contact (***P***) and (***Q***) lie on the same "pseudo insert circle" as shown in Figure 3 (b). In other words, this small circle of the toroidal tool is tangent to both the intersecting surfaces at P and Q. In this case, when the tool is rotated about spin-axis $\hat{\boldsymbol{n}}_{S1}$, there is a unique spin angle for which the tool just touches surfaces $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$without gouging. This footprint location ensures that the tool fits snugly into the region near the common edge and the two contact points are as close as possible to the common edge. This results in the maximum possible material removal in the common edge region.

When the dropped tool finds no intersection with the second surface (say $\boldsymbol{S_2}$), no amount of spin about the spin-axis ($\hat{\boldsymbol{n}}_{S1}$) can yield tangency between the tool and the second surface ($\boldsymbol{S_2}$) (Fig. 3(c)). Similarly, if the tool-drop location (***T***) is such that the pseudo-insert through the first point of contact of dropped tool intersects with the second surface as shown (Turquoise shade) in Fig. 3 (c), no amount spin about spin-axis ($\hat{\boldsymbol{n}}_{S1}$) can eliminate the gouge between tool and the second surface ($\boldsymbol{S_2}$). So the feasible tool-drop positions that can result in gouge free tangency between the rotated tool and the two intersecting surface is restricted between the two tool drop position as shown in Fig. 3 (a) and 3 (b). This range bounded between tool-drop positions $\boldsymbol{T_1}$ and $\boldsymbol{T_2}$ is termed as "*Spin Zone*" as shown in Fig. 3 (d). DSM can yield a number of valid multipoint tool positioning solutions when the tool drop footprint lies within the "*Spin Zone*".

DSM Implementation & Results:

The DSM has been implemented on two pairs of intersecting bi-quadratic Bezier surfaces. Fig. 5(a), (b) show the plot of one such pair of surfaces. Tool path for finish machining along the common edge has been computed at reference lines which are $f_{step} = 2.5\ mm$ apart. Spin zone limits at all such locations are evaluated by using $x_{step} = 1.0\ mm$. Fig. 4 shows trajectories of first and second points of contact for multi-pass finish machining of common edge region between two intersecting bi-quadratic convex Bezier surfaces. At all such footprint locations, the toroidal tool has been dropped on surface S_1 and then rotated to find second point of contact on S_2. Continuous and dotted trajectories indicate the first and second point of contacts respectively. For each instance of the dropped tool, there exists two spin solutions, depending on the direction of spin. This is indicated by twin trajectories on surface S_2.

DSM multi-pass toolpaths for finish machining of common edge region between the test surfaces were also simulated in Maple™ for validation by plotting the surfaces and the tool orientations corresponding to all tool drop locations as shown in Fig. 5(a), (b). All tool positions comprising the multi pass tool paths were found be gouge free.

In addition to graphical verification of the five-axis toolpath data, we also tested it by machining pairs of concave and convex surfaces on aluminum specimens on a DMU-80P Hi-Dyn tilt-rotary simultaneous five-axis machine (Fig. 5(c)).

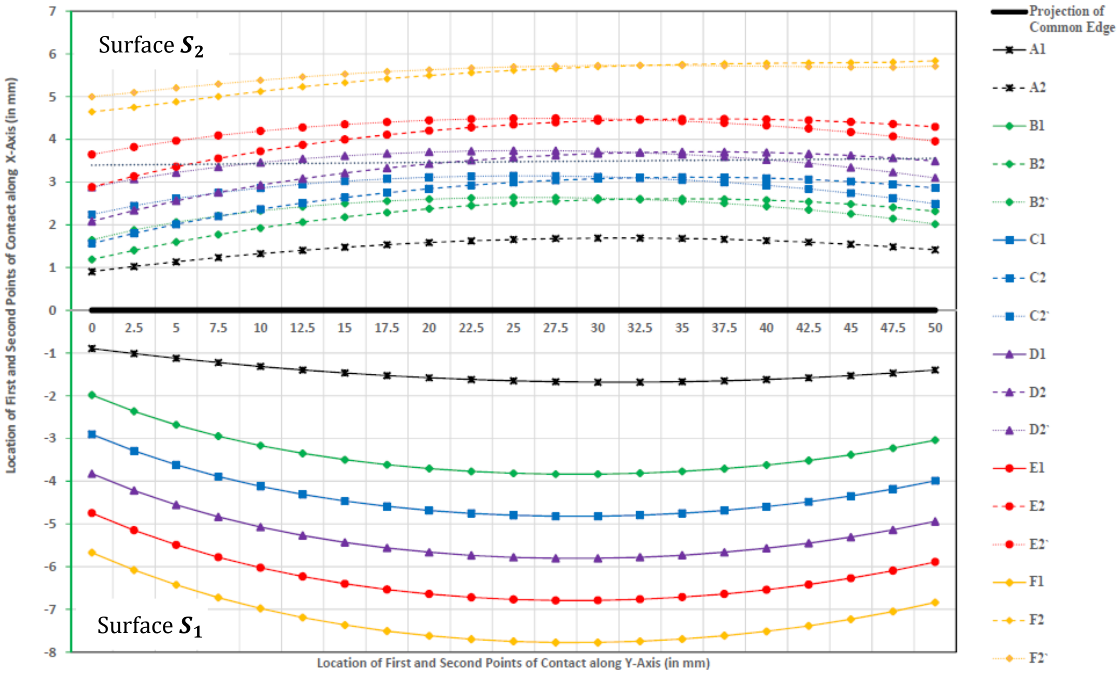
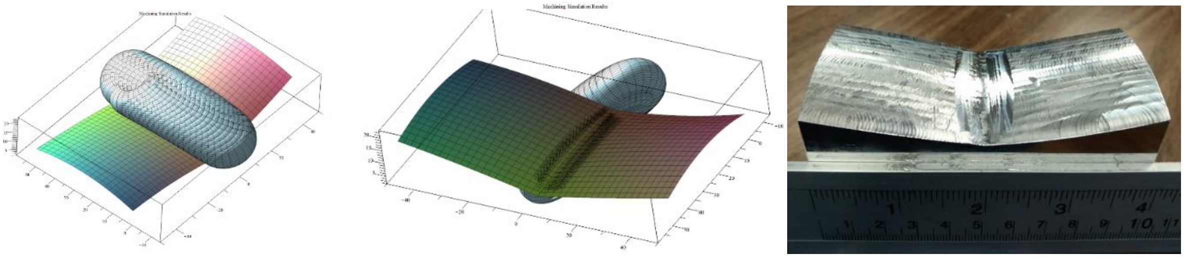


Fig. 4: Trajectories of first and second points of contact for multi-pass finish machining of common edge region between two intersecting Bi-quadratic convex Bezier surfaces. First point of contact on S_1 and second point of contact on S_2.



(a) (b) (c)

Fig. 5: Simulation of multi-pass tool paths for finish machining of common edge between two intersecting Bi-quadratic convex surfaces: (a) Top view, (b) Bottom view and (c) Machined on DMU-80P-Hi-Dyn tilt-rotary simultaneous 5-axis machining.

Conclusions:

Drop tilt method [3] implemented for machining composite surface patches is not able to clean the region of the common edge as well as the zone near the edge on either of the surfaces. Hence DSM is developed to accomplish the finishing of the common edge zone.

Snugly fit DSM tool path removes the maximum material on the common edge without gouging for a given $\boldsymbol{R_i}$ of the toroidal tool. Thus, it is termed as ideal toolpath because the two contact points $\boldsymbol{P}$ and $\boldsymbol{Q}$ maintain the minimum gap for this toolpath. However, this tool path is not as effective in finishing the near common edge region of the two surfaces $\boldsymbol{S_1}$and $\boldsymbol{S_2}$. Thus, generating multiple passes within "*spin zone*" is required to effectively finish the near common edge zone.

For each tool drop position within the "Spin Zone", there are two possible spin solutions depending upon direction of spin angle. One tool orientation leads to removing unmachined material using the leading edge of the tool while the other removes material using the trailing edge.

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