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Process planning for Floor machining of 2½D pockets based on a morphed spiral tool path pattern ☆

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ABSTRACT

This work proposes a process planning for machining of a Floor which is the most prominent elemental machining feature in a 2½D pocket. Traditionally, the process planning of 2½D pocket machining is posed as stand-alone problem involving either tool selection, tool path generation or machining parameter selection, resulting in sub-optimal plans. For this reason, the tool path generation and feed selection is proposed to be integrated with an objective of minimizing machining time under realistic cutting force constraints for given pocket geometry and cutting tool. A morphed spiral tool path consisting of G^1 continuous biarc and arc spline is proposed as a possible tool path generation strategy with the capability of handling islands in pocket geometry. Proposed tool path enables a constant feed rate and consistent cutting force during machining in typical commercial CNC machine tool. The constant feed selection is based on the tool path and cutting tool geometries as well as dynamic characteristics of mechanical structure of the machine tool to ensure optimal machining performance. The proposed tool path strategy is compared with those generated by commercial CAM software. The calculated tool path length and measured dry machining time show considerable advantage of the proposed tool path. For optimal machining parameter selection, the feed per tooth is iteratively optimized with a pre-calibrated cutting force model, under a cutting force constraint to avoid tool rupture. The optimization result shows around 32% and 40% potential improvement in productivity with one and two feed rate strategies respectively.

1. Introduction

Significant use of 2½D pocket machining in aerospace and automotive industries has motivated engineers and researchers to search persistently for new methods that increase process productivity and reliability. Process planning is a critical component in process optimization and improvement and has wide flexibility in choosing the tool path geometry as well as applicable machining parameters. The large number of studies dedicated to the process planning issues for 2½D pocket machining (Banerjee, Feng, & Bordatchev, 2007) only reinstates its enormous research popularity as well as the associated complexities. A typical pocket geometry with length (l), width (w), and height (h) can be represented in terms of elemental machining surface: Floor, Corner and Wall, as shown in Fig. 1a with their connectivity shown with the adjacency graph in Fig. 1b. Floor machining operation involves the maximum material removal and machining time compared to the other EMSs. The primary planning requirement is that the tool completely sweeps the entire Floor surface area in minimum possible time without over-limit tool wear and rupture. In order to perform Floor machining, the following parameters have to be simultaneously considered – feed rate (V), step over (s), tool diameter (d) and the material (d_m) to be left from the 2½D pocket boundary as shown in Fig. 1c. The major planning tasks involved are tool selection (D'Souza et al., 2001; Lee & Chang, 1995), tool path generation (Bieterman & Sandstrom, 2003; Bruckner, 1982; Choi & Kim, 1997; Gupta, Saini, & Yao, 2001; Stori & Wright, 2000; You, Sheen, & Lin, 2001) and machining parameter selection (Bae, Ko, Kim, & Cho, 2003; Kloypayan & Lee, 2002; Lee & Cho, 2003; Smith, Cheng, & Zamudio, 1991; Weck, Altintas, & Beer, 1994). The tool selection involves determining the tool diameter, tool path geometry generation deals with cut pattern, path interval and axial cuts and machining parameters to be selected are radial and axial depth and feed rate.

Recently, high speed milling has become popular to minimize machining time and maintain high material removal rates. However fluctuations in the feed rate vector leads to significant jerks in the machine tool. It would seem that high speed machining for generating Floor is suitable, if a tool path can be selected such

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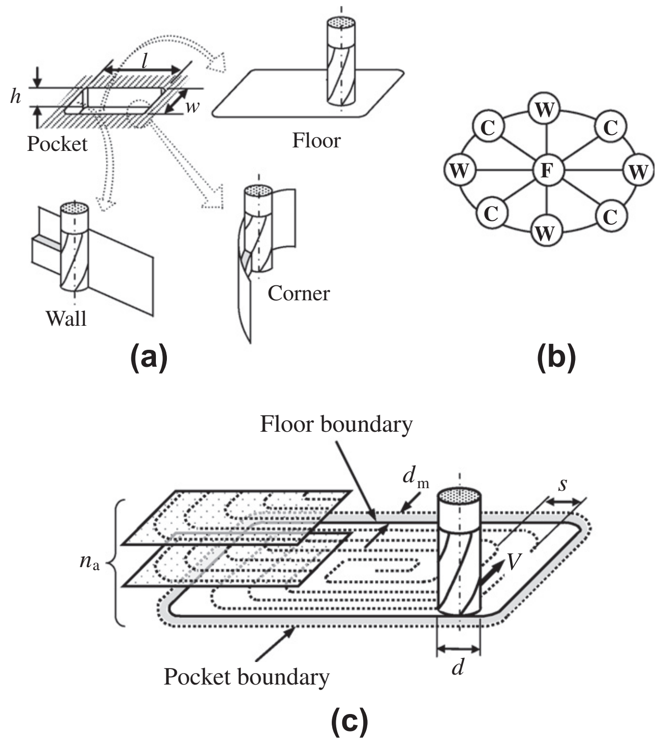

Fig. 1. Representation of 2½D pocket in terms of: (a) elemental machining surfaces; (b) adjacency graph; and (c) Floor.

that feed rate fluctuation along it is minimized. For this purpose, a spiral tool path is being considered in this work due to its capability of achieving smoother and consistent machining. The feed rate along such a tool path can be smoothly adjusted (Bieterman & Sandstrom, 2003) owing to its consistent cutter engagement (Stori & Wright, 2000) and lower curvature with G^1 continuity. The spiral cut pattern had been generated by creating the offsets of the pocket boundary (You et al., 2001) with a consistent engagement angle and minimal curvature (Stori & Wright, 2000). A partial differential equation based morphed spiral cut pattern (Bieterman & Sandstrom, 2003) has been proposed which can overcome the short comings of previous methods, such as complicated self-intersection calculations and limited pocket geometries. However, the morphed spiral tool path is represented as a spline interpolation which in spite of tremendous research and development effort is still not widely available in common commercial Computer Numerical Control (CNC) machine tools. This limits the applicability of such spline-based tool path trajectory to only a limited number of machine tools.

To maximize the practical applications of tool path composed of higher order splines, the tool path needs to be converted into a combination of the piecewise continuous circular and linear segments which can readily be implemented by the common CNC Linear interpolation functions. This can be achieved with the help of biarc (Bolton, 1975; Su & Liu, 1989) and arc spline (Meek & Walton, 1992) concepts, which are G^1 continuous composite curves using two arcs and an arc and a line, respectively. The G^1 continuous tool path enables a constant feed rate without slowing down or stopping the tool. According to a maximum permissible limit on the feed rate. This feed rate limit can be calculated based on the geometry of the tool path and the dynamic properties of the machine tool servo system (Pateloup, Duc, & Ray, 2004).

In this work, the process planning of Floor machining is to be presented. The planning task of tool path generation addressing the geometric and the machining issues is presented in Section 2. The machining parameter selection for the minimization of machining time under a cutting force constraint is discussed in Section 3. In Section 4, the calculated tool path length and measured dry machining time obtained by the proposed tool path is compared with other commercially available strategies. The simulation of instantaneous cutting forces targeting optimal feed per tooth selection with single and double feed strategies is also provided. In the last section, contributions of the present work and future recommendations are presented.

2. Tool path generation

The primary requirement of the tool path generation for Floor machining is to completely sweep area within its boundary with the selected tool as efficiently as possible, i.e. with minimum machining time. To ensure minimum machining time, a consistent cutter engagement, cutting conditions and smooth transition of cutting directions are desirable, especially in the context of high speed machining. This will facilitate continuous tool movement without slowing down or stoppage during the cut and generate near uniform cutting force profile. The spiral cut pattern is suited for the above purpose as it provides low curvatures with G^1 continuity and consistent cutter engagement (Bieterman & Sandstrom, 2003; Stori & Wright, 2000; You et al., 2001). Thus, in this work, a spiral cut pattern has been selected rather than a zigzag or contour parallel pattern for Floor machining.

2.1. Spiral cut pattern

An existing approach (Bieterman & Sandstrom, 2003) of solving the eigen-value problem for an elliptic PDE, subject to Dirichlet's boundary conditions, has been adopted to generate the morphed spiral cut pattern. The solution contours for a rectangular pocket are generated with the help of MATLAB™ PDE Toolbox. In order to embed practical heuristics into tool path generation, a maximum step over distance (s_{max}) is selected based on the tool/workpiece material and tool geometry. This distance is to be maintained along the direction of the maximum variation between consecutive contours with the help of computer programming. In case of the rectangular pocket, the maximum variation occurs along its diagonal. It was observed that relative percentage error between the ideal maximum (s_{max}) and actual maximum (s_j) step over distances for each consecutive contour varies with the numerical mesh resolution used for the computing the solution contours, as shown in Fig. 2. The figure suggests that higher mesh resolution will provide lower error but at the cost of higher computational time and lower computational accuracy. Thus, a mesh resolution of 512×512 is selected as a trade-off between computational time and accuracy. The s_{max} is selected to be equal to the maximum radial depth of cut (d_r) shown in Fig. 3. The maximum value of d_r is selected as $d/4$ where d is the diameter of the given tool, based on the preferred radial depth of cut for peripheral end milling (Technical Staff, 1997). At a different level of integration, the radial depth can be a free parameter which could be optimized for specified objective functions and constraints.

Once the contours have been obtained from the numerical solution of the PDE, 2^N equi-angular ($\Delta\theta$) points ($\mathbf{P}$) are created on each contour to generate the spiral points ($\mathbf{S}$) between the solution contours with a linear relationship as shown in Fig. 4 and given by,

$$\mathbf{S}_j^i = [\mathbf{P}_{j+1}^i - \mathbf{P}_j^i] \cdot \frac{i \cdot \Delta\theta}{2\pi} \tag{1}$$

where i is the angular index with value from 1 to 2^N, j is the index of the contour with $j = 0$ corresponding to the innermost contour. It is evident that the higher the value of N, the smoother the generated