Journal of Materials Processing Technology 233 (2016) 29–43

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Trochoidal machining for the high-speed milling of pockets

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ARTICLE INFO

Article history:
Received 6 September 2015
Received in revised form 3 January 2016
Accepted 30 January 2016
Available online 8 February 2016

Keywords:
High-speed milling
Trochoidal machining
Milling force

ABSTRACT

When machining the pocket of a mould in high-speed milling mode, the tool load at a pocket's narrow area or corner may sharply increase because of the presence of a higher amount of material to be cut. A trochoidal machining method considering milling force, machining tool, and pocket geometry is proposed in this paper. First, a method for the geometric modeling of the engagement angle in trochoidal machining is proposed. Maximum and mean values of the milling force are analysed; meanwhile, the corresponding relationship between the milling force curve and the engagement angle curve during the trochoidal machining process is analysed. Based on fundamental experiments on trochoidal machining, results for the milling force and tool wear are obtained; then, a proper control strategy for cavity trochoidal milling machining is proposed. Based on this control strategy for trochoidal milling machining, two realisations of cavity trochoidal milling machining are proposed. Finally, comparison experiments on cavity machining are conducted. Compared with the feedrate adjustment method, trochoidal machining provides better control over the milling force and tool wear at corners and narrow slots. The milling force and machining vibrations are smaller, and the tool wear is substantially reduced.

1. Introduction

High-speed milling provides various benefits in terms of improved production efficiency, machining precision, surface quality, etc. It has been successfully applied in the mould industry and promotes the rapid development thereof. Contour-parallel tool paths are a common high-speed milling method for cavity moulds, where the tool path is generally calculated based on the contour offset and intersection. However, corners and narrow areas such as slots may easily appear between contours. If no special treatments are applied, the following issues can frequently arise in high-speed machining: (1) the engagement angle or engagement arc length between the tool and uncut materials can be greatly increased, resulting in a sharp increase in the contact material. (2) The tool load amount can be much higher at a corner or slot, resulting in a greater fatigue or damage to the tool. These problems are particularly serious in the high-speed milling of harder materials.

The engagement angle and cutting load variations have generated concern by scholars. Various studies have been conducted, including the analysis and modelling of the engagement angle, milling force, and other aspects. Kline et al. (1982) presented a mechanistic model for the force system in end milling and stated that varying the cutting engagement and chip thickness could cause variations in the cutter load. Choy and Chan (2003a,b) reported that the instantaneous cutter sweep angle (CSA) is a suitable parameter for studying chip load in 2.5D pocket milling and proposed a comprehensive modeling method; experiments showed that the model can accurately predict a cutter load pattern at cornering cut. Wei et al. (2010) proposed an effective milling force model for pocket machining and pointed out that the varying feed direction and cutter engagement could affect the milling force for the entire process. These studies show that the close relationship between tool contact and load changes during machining process. This relationship is used as the basis to establish methods for reducing cutting load, such as the adjustment of the cutting parameters or trajectory.

Two major approaches, namely, the adaptive control and geometry modification of the tool path, to addressing the cutting load variation problem can be identified. The adaptive control approach focuses on controlling the cutting performance by instantaneously adjusting the cutting parameters when milling the work pieces. Spence and Altintas (1994) developed a simulation system based on constructive solid geometry (CSG) and concluded that the feed rate can be automatically scheduled to satisfy force, torque, and part dimensional error constraints. Tarng and Shyur (1993) argued that cutting stability is greatly dependant on the radial depth of cut and proposed a method for identifying the radial depth of cut in pocket machining; they concluded that the feedrate can be adjusted accordingly to maintain a constant material removal rate.

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http://dx.doi.org/10.1016/j.jmatprotec.2016.01.033
0924-0136/

Bae et al. (2003) assumed that the cutting force is a function of two major independant variables, namely, 2D chip-load and the feedrate; a simplified cutting model was proposed to adjust feedrate for pocket machining. Liu et al. (2015) presented a feedrate optimisation strategy with multiple constrains including relative chip volume, milling force, and cutter deflection. The experimental results demonstrated that the optimised feedrate can satisfy the requirements for a pocket milling process. The adaptive control approach, which is used to adjust the instantaneous contact relationship between cutter and the workpiece, exhibits a certain effect on controlling the cutting force and protecting the cutting tools during machining. Because the cutting force and vibration may increase almost instantaneously at a sharp corner or a narrow slot, the adaptive control approach could help to reduce to a certain degree but not completely avoid the negative influences.

The second approach is the treatment of the trajectory by changing the track form. Zhao et al. (2007) demonstrated that residual materials at the corner can be effectively removed by inserting a biarc curve. Through the technique, the tool may be subjected to high cutting loads because the tool enters the corner in a direct manner. Choy and Chan (2003a,b) inserted bow-like tool path segments at a corner and concluded that the improved tool path can clear the accumulated material and reduce the cutting load at pocket corners; this progressive cutting method can effectively control the milling load. Elber et al. (2005) considered the need for C^1 continuous tool paths and presented a pocket tool path containing a series of circular arcs; this method mainly focuses on the geometrical analysis and discussion. Ibaraki et al. (2010) proposed that the materials of the medial axis areas of the pocket should be removed by trochoidal grooving to effectively control the tool load during the late milling stage. Ferreira and Ochoa (2013) presented a method to generate trochoidal tool paths for pocket milling process with multiple tools and concluded that the method can avoid the momentary increments in the radial depth of cut. The second method is more effective in decreasing the load variation and protecting the milling tool; however, few papers have comprehensively considered the milling force, cutting tool, and processing.

Trochoidal machining for high-speed milling pockets can be categorised as the second method. It is a method of progressively cutting away material and is very suitable for milling narrow areas or sharp corners, where the cutting load changes considerably (Fig. 1). In recent years, certain commercial CAM software has included trochoidal machining methods. Several scholars have also launched corresponding studies on trochoidal machining. Through process experiments, Uhlmann et al. (2013) holds that a trochoidal milling strategy for TiAl6V4 workpieces offers considerable potential to improve energy consumption and process time during production. For difficult-to-machine materials such as Nickel-based superalloys, Pleta et al. (2014) provided a comparison of trochoidal milling with a traditional milling technique. They believe that the process of trochoidal machining can result in improved productivity and efficiency. Aiming at the workpiece surface with holes and bosses, Otkur and Lazoglu (2007) proposed an approach to model the milling force for trochoidal milling. The experimental results demonstrated the good agreement between the predicted forces and the measured forces. Rauch et al. (2009) investigated the trochoidal model which infers curvature and tangency continuity, and concluded that the cutting time and tool life can be effectively improved in a high dynamics machining tool. Rauch and Hascoet (2007) developed algorithms that can be used to generate trochoidal and plunge cutting trajectories for pocket milling. The results of this study lead to a better definition of the strengths and weaknesses of trochoidal milling and plunge cutting strategies in rough machining of aluminium alloys with a focus on optimizing the choice of strategies. In these trochoidal models, the trochoidal circles normally present equal diameters.

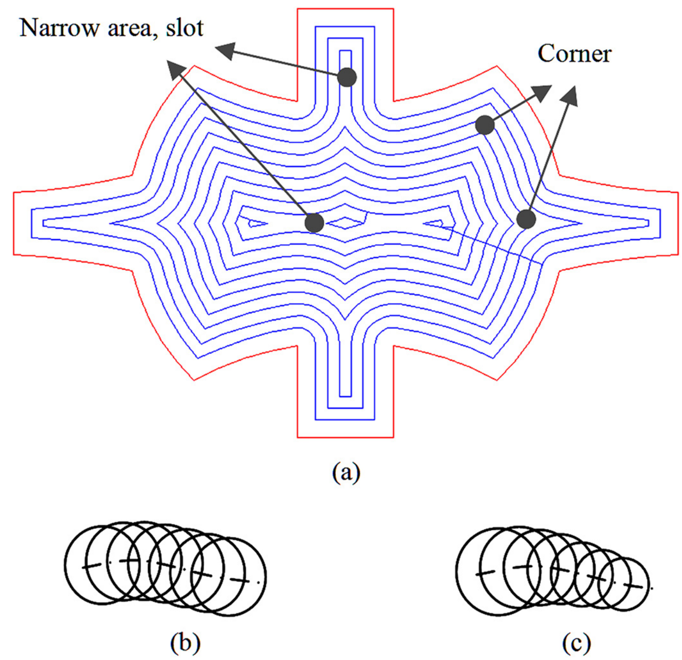

Fig. 1. Trochoidal machining for a pocket: (a) narrow areas or sharp corners in a cavity; (b) trochoid with isometric circles; and (c) trochoid with variable circles.

In this paper, the trochoidal definition is expanded to include two types of trochoidal machining: isometric circle trochoid (Fig. 1b) and variable circle trochoid (Fig. 1c). Ibaraki et al. (2010) reported that the medial axis areas of a pocket should be removed by trochoidal tool paths prior to high-speed contour-parallel cutting. The experiments demonstrated improved machining efficiency and tool wear. In the study, the machining parameters, such as the size or distance of trochoidal circles, are specified based on experience. Unsuitable parameters may cause reduced efficiency or increased the tool load. In the present work, a trochoidal model and a control strategy for controlling parameters are proposed and used to generate several kinds of pocket trochoidal paths.

Attempting to address the processing problems in milling narrow areas or corners in a pocket, this paper will present research on trochoidal machining. The milling forces, tool wear, tool path and cavity geometry will be comprehensively considered. The remainder of the paper is organised as follows. The modelling of the engagement angle and milling force in trochoidal machining is presented in Section 2. The control strategies for trochoidal machining are presented and analysed in Section 3. The realised methods of trochoidal machining in pockets are given in Section 4, followed by experimental identification in Section 5 and conclusions in Section 6.

2. Modelling of the engagement angle and force in trochoidal machining

2.1. Basic concepts

The engagement angle represents the contact geometrical relationship between the tool and the uncut material of the workpiece. As the tool travels along the tool path, the engagement angle continuously varies, as shown in Fig. 2. The engagement angle will reach its maximum value in the concave corner area. Accordingly, the amount of material to be cut will reach a maximum at the concave corner, similar to the milling force. As mentioned by Choy and Chan (2003a,b), the cutter load is directly related to the cutter engage arc length or the engagement angle. Therefore, the engagement angle