International Journal of Machine Tools & Manufacture 88 (2015) 184–193

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

Precise prediction of forces in milling circular corners

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ARTICLE INFO

Article history:
Received 22 December 2013
Received in revised form
3 September 2014
Accepted 8 September 2014
Available online 18 September 2014

Keywords:
Circular corner milling
Cutting force prediction
Engagement angle
Undeformed chip thickness
Iteration algorithm

ABSTRACT

Pocket corner is the most typical characters of aerospace structure components. To achieve high-quality product and stable machining operation, manufacturer constantly seek to control the cutting forces in pocket corner milling process. This paper presents the cutting force in corner milling considering the precision instantaneous achievements of tool engagement angle and undeformed chip thickness. To achieve the actual milling tool engagement angle in corner milling process, the details of tool–corner engagement relationship are analyzed considering the elements of tool trajectory, tool radius, and corner radius. The actual undeformed chip thicknesses in up and down milling operations are approached on account of the trochoid paths of adjacent teeth by a presented iteration algorithm. Error analysis shows that the presented models of tool engagement angle and undeformed chip thickness have higher precision comparing with the traditional models. Combined with the cutting force coefficients fitted by a series of slot milling tests, the predicted cutting force in milling titanium pocket with different corner structure and milling parameters are achieved, and the prediction accuracy of the model was validated experimentally and the obtained predict and the experiment results were found in good agreement.

1. Introduction

Circular corner milling operation in machining pocket structure is widely used in aerospace manufacturing industry. Reliable quantitative predictions of the cutting force components in corner milling operations are essential for determining the power requirements, machined component geometrical errors or deviations, chatter vibration characteristics and strength requirement of the cutting tool.

Corner machining has been considered as one of the most critical pocketing tasks. Both of small corner radius and high ratio of height to corner radius are widely used to reduce the weight of the aerospace components. The cutters with smaller radius and higher ratio of height to radius are often selected for finishing corner, unfortunately which is usually unstable in the milling process. Furthermore, in corner machining, varying radial depth of cut is commonly encountered by the end mill when it enters and exits the pocket corner, which will lead to noticeable changes in the cutting force, especially for titanium and so on hard machining materials components. Large cutting forces usually cause cutter deflections, bad surface quality, poor dimension accuracy, cutter breakage, even parts and machine tool damage.

One of the fundamental obstacles in optimizing the cutting situation in corner milling is to predict the cutting force correctly. In recent years, developed cutting force models [1–3] are acquired on the conditions of end milling. And many researchers focused on the cutting forces prediction of varying machining conditions [4–6]. Then, some cutting force prediction investigations in corner milling are put forwarded. Zhang et al. [7] proposed an approach to predict the cutting forces in peripheral milling of circular corner profiles in which varying radial depth of cut was encountered. Li and Liu [8] presented a strategy to predict cutting force variations for both inner and outer circular corner milling. Wei et al. [9] studied an approach to predict the cutting force for the whole finishing process of pocket machining. However, the actual undeformed chip thickness as an important factor affecting the cutting force in the corner milling process has not been focused on in these researches.

A number of authors have studied the approximation of undeformed chip thickness in straight line milling and reported various models [10–14]. After that, some new methods for determining the undeformed chip thickness in milling were proposed [15–18]. Some researchers [19–22] gave various strategies for calculating the instantaneous undeformed chip thickness in corner milling and concluded that the undeformed chip thickness formed in case of circular interpolation is different from the one in linear interpolation with the same cutting conditions. In this work, different from previous research, an actual undeformed chip thickness model based on real adjacent teeth trajectories will be proposed for cutting force prediction in circular corner milling.

This paper attempts the real calculation of tool–corner engagement angle considering the geometrical characters of tool trajectory, corner radius and tool radius, respectively. And then present

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http://dx.doi.org/10.1016/j.ijmachtools.2014.09.004
0890-6955/

a precision approach of the actual undeformed chip thickness for up and down corner milling operations with respect to the instantaneous immersion angle. The actual tool trajectory and the geometrical relationship between the adjacent teeth in corner milling are analyzed and modeled for calculating actual chip thickness. A series of titanium slot milling experiments are carried out to achieve the cutting force prediction coefficients. Finally, a titanium component is designed and machined to verify the cutting force prediction with respect to the actual tool–corner engagement angle and undeformed chip thickness. The rest of the paper is organized as follows. The prediction of cutting force in circular corner milling is presented in Section 2. The geometry details of circular corner milling are presented and analyzed in Section 3. The determination of the instantaneous engagement angle and undeformed chip thickness are given in Sections 4 and 5, respectively, followed by experimental identification in Section 6 and conclusion in Section 7.

2. Cutting force model for circular corner milling

According to the mechanistic force model [6], differential cutting forces acting on an infinitesimal tool element with height dz in tangential ($dF_{t,j}$), radial ($dF_{r,j}$), and axial ($dF_{a,j}$) are expressed as follows:

$$\begin{cases} dF_{t,j}(\phi,z)=[K_{tc}h_j(\phi_j(z))+K_{te}]dz \\ dF_{r,j}(\phi,z)=[K_{rc}h_j(\phi_j(z))+K_{re}]dz \\ dF_{a,j}(\phi,z)=[K_{ac}h_j(\phi_j(z))+K_{ae}]dz \end{cases} \quad (1)$$

where, chip thickness $h_j(\phi,z)$ is the instantaneous undeformed chip thickness, and $\phi_j(z)$ is the instantaneous immersion angle position for flute j at axial depth of z, which can be given as $\phi_j(z)=\phi+j\phi_P-(2\tan\beta/D)z$. And, β is the helix angle, and pitch angle ϕ_j is defined as $\phi_P=2\pi/N$, where N is the tooth number. The K_{tc}, K_{rc}, and K_{ac} are the force element coefficients due to the cutting process, and K_{te}, K_{re}, and K_{ae} are the force element coefficients due to the edge forces, which can be determined by a series of milling experiment [6]. Then, the tangential, radial and axial forces given by Eq. (1) can be resolved into feed (x), normal (y) and axial (z) directions using the transformation as follows:

$$\begin{cases} dF_{x,j}(\phi_j(z))=g(\phi_j)[-dF_{t,j}\cos\phi_j(z)-dF_{r,j}\sin\phi_j(z)] \\ dF_{y,j}(\phi_j(z))=g(\phi_j)[+dF_{t,j}\sin\phi_j(z)-dF_{r,j}\cos\phi_j(z)] \\ dF_{z,j}(\phi_j(z))=g(\phi_j)[+dF_{a,j}] \end{cases} \quad (2)$$

where, $g(\phi_j)=1$ while $\phi_{st}\le\phi_j(z)\le\phi_{ex}$, otherwise $g(\phi_j)=0$. ϕ_{st} and ϕ_{ex} are the entry angle and exit angle of the tool–workpiece engagement area, respectively. Consequently, the total instantaneous forces on the cutter at engagement angle position ϕ would be expressed as follows:

$$F_x(\phi)=\sum_{j=0}^{N-1}F_{xj};F_y(\phi)=\sum_{j=0}^{N-1}F_{yj};F_z(\phi)=\sum_{j=0}^{N-1}F_{zj} \quad (3)$$

Obviously, the range of tool–workpiece engagement area, i.e., ϕ_{st} and ϕ_{ex} and the instantaneous undeformed chip thickness, $h_j(\phi,z)$ are the significant elements in predicting the cutting force in circular corner milling operation, which are distinct from the straight feeding milling operation and will be presented in the following sections.

3. Geometry details in circular corner milling operation

To achieve the predictions of tool engagement angle and undeformed chip thickness, the geometry details of the circular corner milling process should be analyzed firstly. It is obvious that

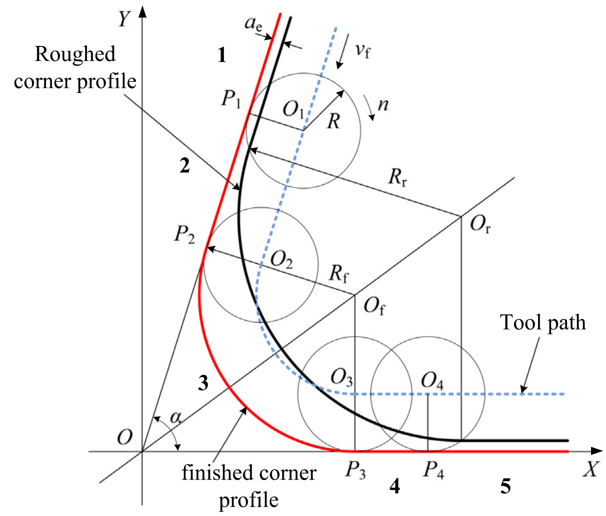

Fig. 1. Split process of circular corner milling.

the tool feed trajectory in circular corner milling is distinguished from linear milling operation. In linear milling operation, the feed rates of the tool axis and the tool tip are the same with each other and the tooth tip trajectory is a trochoid arc path with tool axis linear feed movement as the middle line.

To demonstrate the details of geometrical characteristic in corner milling operation, a typical corner milling process with a global Cartesian coordinate is set up as shown in Fig. 1. An existing circular corner profile with radius R_r, which is generated after roughing milling process, will be finished to circular corner profile with radius R_f by an end-mill with radius R. The roughed corner profile is marked as the black line combined with straight lines and arc segments. And the finished corner profile is marked as the red straight-arc combination lines. Furthermore, tool trajectory is marked as blue dashed line. The end mill is driven along arc tool path at a feed speed of V_f with the spindle rotation rate n. The offset distance a_e is the perpendicular distance from the roughed profile to the finished profile before end mill enters the corner trajectory. The corner angle, or the inclined angle in this corner milling process is defined as the angle between the approaching linear trajectory and the deviating linear trajectory of the end mill, labeled as α in this research (as shown in Fig. 1).

According to the variety of the radial depth of cut a_e along the tool feed path, the finishing operation with respect to the tool trajectory in corner milling process can be separated into five segments as follows.

(1) Before position O_1, steady linear milling.
In this segment, the tool feeding path and the roughed surface profile, i.e., unmachined surface are both straight line and parallel with each other. The cutting off-set between roughed surface and finished surface a_e is constant.

(2) From position O_1 to O_2, linear feed milling process with increasing radial depth of cut a_e.
In the segment from O_1 to O_2, tool axis still feeds forward following a linear path. However, the roughed surface profile turns to be an arc, in other words, the off-set a_e becomes a variable when tool axis crossing position O_1 and increases with the tool feeding forward. In this segment, the finished surface profile is a straight line parallel with tool feed trajectory.

(3) From position O_2 to O_3, arc feed milling process with varying radial depth of cut.
Both of the finished surface profile and roughed surface profile are arcs, and the off-set a_e ascend in first and then descend. It is obvious that the tool feeding path follows an arc trajectory.