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ORIGINAL ARTICLE

A new approach for predicting wear overlap geometry in ball end finish milling

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Abstract
The inclination angles of sculptured surface and tilting angles of 5-axis machining change cutting time distributions (CTD) on cutting contact (CC) points. The models of element wear (EW) function of the CTD on each CC points are overlapped to form wear overlap (WO) geometry. However, the WO geometry has not been taken into account in most current tool wear models. This paper proposes a new approach for modeling of the WO geometry associated with the overlapping zones in the 5-axis machining of sculptured surfaces. The EWs in response to CTD at each CC points are modeled using probability density function. The EW is changed to the linear function of time by deforming the tool wear unit. Afterward, for each overlapping point, the WO value is calculated by using the method of the linear addition of linearized EWs. Then, the WO geometry is obtained by the inverse deformation of the unit. The proposed approach is demonstrated and validated through a case study. The predictions of WO geometry present good accordance with experimental observations in constant tilting angle and flat convex surface finish milling process.

Keywords Cutting time distribution · Element wear · Tool wear unit deformation · Overlapping zone · Wear overlap geometry

1 Introduction

The 5-axis ball end milling are commonly used in generating complex shapes on high hardened steels in various industries such as aerospace, automotive, and die-mold industries. A complex sculptured surface involves a continuous variation in surface inclination angles and cutting contact (CC) points, which generates very complex overlapping zones in the milling process. During the curved surface milling process, there is always tool wear associated with surface inclination angles and overlapping zones, which not only affects the machining accuracy but also the integrity of the machined surface. Therefore, it is necessary to consider the effect of surface inclination angle and overlapping zone on the tool wear during machining. In reality, tool wear is one of the key challenges in machining of hardened materials which are commonly used in precision engineering.

With 5-axis ball end milling process, a complex curved surface is composed of many curved surfaces with different curvatures. The inclination angles change during the curved surface milling process, owing to changes in the surface normal vector, thus affecting the tool wear and surface integrity. Ko et al. [1] have focused on the inclination angle and cutter path by considering the cutting force, surface roughness, and tool wear. The results indicated that an inclination angle of 15° was optimal and that horizontal downward milling was the best cutter path. Gani et al. [2] have discussed the effect of tool orientation on the cutting process in 5-axis milling by using the geometric model of machining process. Daymin et al. [3] reported that the best surface finish was obtained when inclination angle of workpiece was 15°, and the mean surface stress decreased slightly as the inclination angle increased. Lim [4] has focused on the high-speed finish milling and investigated the effects of four different cutter paths on surface roughness. The results indicated that the horizontal downward cutting orientation satisfied the processing requirements in multi-axis CNC machining. Zhou et al. [5] have discussed that the complex curved surface design technology and CNC machining

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technology and they predicted the development tend of complex curved surfaces. Yao et al. [6] investigated the effects of tool orientations and surface curvature on surface integrity experimentally during the finish milling of TC17 titanium alloy, and reported that the surface roughness in both directions was better when the rotational angle was within the range of 0°~90° and with a constant inclination angle. Chen et al. [7] investigated the machining characteristic under various inclination angles; they found that the inclination angle has a great influence on the texture, roughness, and topography of the machined surface, which can be used as indictors of tool wear.

Cutting parameters have significant impact on tool wear in a machining process, and empirical cutting tests are usually used to establish tool wear model. Davim [8] used multiple linear regressions to obtain an empirical model of correlation of tool wear in terms of cutting velocity, feed rate, and cutting time on turning metal matrix composites. Özeal et al. [9] developed tool wear model by using multiple linear regression and neural networks. They compared the predicted results with non-training experimental data and found good conformity. An analytical model of tool flank wear considering cutting parameters and tool-workpiece material was proposed by Huang et al. [10], which also investigates tool wear mechanism for CBN tool in finish hard turning of steel. Bh et al. [11] developed tool wear model using response surface methodology in respect of cutting parameters in hard turning of AISI D3 hardened steel. They also analyzed the adequacy of the model with ANOVA.

To understand tool wear behavior in the machining process, tool wear monitoring methods have been developed. Girardin et al. [12] detected the tool wear by monitoring the variation in rotational frequencies on different teeth of the tool. Zhang and Zhou [13] used shape mapping method to obtain an empirical model of correlation of tool wear in terms of cutting parameters in ball end milling of stainless steel. Zhang et al. [14] conducted online tool wear measurement system to check tool wear under constant inclined surface milling, and the tool wear can be computed based on the detected wear edge points. Nouri et al. [15] estimated the tool wear by tracking the force model coefficients in real time during the cutting process and reported an overall tool wear parameter for the wear monitoring. Luo et al. [16] introduced a new multi-axis milling strategy for free-form surfaces based on the idea of shifting the active cutting edge on the cutter, and their results showed that a large improvement of tool life can be achieved by the proposed machining strategy.

According to the above literatures, a group of researchers have focused on investigating tool wear with consideration of cutting parameters, cutter paths, inclination angles, the active cutting edges, and so on. It is common to employ constant values of local variables (maximum or average values), which often results in over or under estimation of the tool wear value. However, the determination of the tool wear geometry under overlapping zones is mentioned a little. Normally, manufacturing process in generating complex shapes, the instantaneous CC point along the cutting edge is changed with the variety of the instantaneous surface inclination angle, which in turn generating very complex overlapping zones. All of the above-mentioned suggests that it is important to take instantaneous CC points and overlapping zones into account in order to accurately model wear evolution.

To address this issue, the new approach proposed in this paper has been focused on WO geometry modeling. The modeling approach is proposed by including the condition that overlapping zones on tool flank surface vary randomly because of the variety of the instantaneous CC points and its corresponding cutting time distributions (CTD) during the milling process. Probability density function, linear deformation (LD), and inverse deformation (ID) are the foundations of this new approach. The development of new approach is demonstrated and validated through a case study on the hardened HP1 steel with coated carbide ball end mill.

2 Methodology for WO geometry modeling

Finish milling with a coated carbide ball end mill involves continuous variation in the surface inclination angles, thereby introducing complexities in predicting tool wear under the overlapping zones. This section describes the methodology to estimate wear overlap (WO) geometry in the ball end milling process. The developed approach is presented schematically in the flowchart of Fig. 1. This approach differs from the conventional method in that it considers the CTD on CC points and overlapping zones in the tool wear analysis. As seen in Fig. 1, the proposed approach is carried out in five sequential steps; (1) CTD, (2) element wear (EW) model, (3) LD of the EW unit, (4) WO approach, and (5) ID of the WO unit. The details of the proposed approach are elaborated next.

2.1 CTD

Sculptured surface and 5-axis machining involves a continuous variation in surface inclination and title angles, which generates very complex overlapping zones in finish milling process. In reality, the fixed operating conditions in finish milling involving spindle speed, feed rate and step-over and normal depths. Therefore, the only thing to be determined is the CTD on the CC points. With the progress of tool wear in the constant tilting angle milling, the CTD on the each CC point is a discrete distribution. By comparison, when milling flat convex surface, the total cutting time is distributed to each instantaneous CC points; thereby, the CTD on the CC points are continuous distribution. Zones are called overlapping as each of them has at least one common CC point with the