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Analytical modeling of turn-milling process geometry, kinematics and mechanics

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ABSTRACT

This paper presents an analytical approach for modeling of turn-milling which is a promising cutting process combining two conventional machining operations; turning and milling. This relatively new technology could be an alternative to turning for improved productivity in many applications but especially in cases involving hard-to-machine material or large work diameter. Intermittent nature of the process reduces forces on the workpiece, cutting temperatures and thus tool wear, and helps breaking of chips. The objective of this study is to develop a process model for turn-milling operations. In this article, for the first time, uncut chip geometry and tool–work engagement limits are defined for orthogonal, tangential and co-axial turn-milling operations. A novel analytical turn-milling force model is also developed and verified by experiments. Furthermore, matters related to machined part quality in turn-milling such as cusp height, circularity and circumferential surface roughness are defined and analytical expressions are derived. Proposed models show a good agreement with the experimental data where the error in force calculations is less than 10% for different cutting parameters and less than 3% in machined part quality analysis.

1. Introduction

Turning and milling operations are widely used in conventional machining processes. Turn-milling is a relatively new process which combines turning and milling operations offering some clear advantages such as interrupted cuts and chip breaking [1]. Interrupted cutting decreases the contact time and allows the cutting tool to cool down which in turn reduces tool wear and increases tool life. Thus, turn-milling can offer increased productivity for difficult-to-machine materials such as high temperature alloys as well as parts with large diameters which cannot be rotated at high speeds.

Academic studies on turn-milling have started in 1990 by Schulz et al. [2] who classified turn-milling operations in two categories: orthogonal and co-axial. This work dealt with eccentricity in orthogonal turn-milling, chip geometry and geometrical accuracy. Recent studies on turn-milling, on the other hand, have generally focused on surface quality of finished product. In their experimental study Choudhury and Mangrulkar [3] carried out a series of orthogonal turn-milling experiments on a vertical milling machine, obtained surface roughness data and compared it with those obtained by conventional turning. They found that the surface quality obtained by orthogonal turn-milling is 10 times better than those obtained by conventional turning. Choudhury et al. [4] studied again the surface roughness in orthogonal turn-milling but this time they compared the results with those obtained by conventional milling. In addition, they also predicted the surface roughness by means of experimental design. Another surface roughness study was done by Vedat et al. [5] who analyzed the surface roughness in tangential turn-milling achieving very good surface quality which is comparable to grinding. Kopač and Pogačnik [6] investigated the effect of eccentricity on surface quality in turn-milling concluding that surface roughness R_a in eccentric turn-milling is much better than that the one in centric turn-milling. Yuan and Zheng [7] tried to model the surface roughness and analyze the influencing factors emphasized the effect of eccentricity on surface roughness.

Besides surface roughness studies, Neagu et al. [8] analyzed the kinematics of orthogonal turn-milling from roundness, cutting speed and functional tool geometry point of views. As a conclusion they claimed that turn-milling can achieve up to 20 times higher productivity than conventional turning in roughing of straight shafts. In their study Kopac and Pogacnik [9] examined the effect of the entry and exit conditions, and found out that the tangential entrance was better for tool life.

Turn-milling has attracted more attention in recent years. In

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2011 Filho [10] conducted orthogonal turn-milling experiments on a five axis machining center measuring cutting forces and comparing them with analytical model predictions for plunge turn-milling. Zhu et al. [11] developed two mathematical models that describe surface roughness and topography during orthogonal turn-milling and performed a series of experiments to verify the models, finally they proposed some parameter selection criteria based on the theoretical and experimental result. Reduced tool wear is another advantage of turn-milling owing to intermittent cutting where cutting temperatures are expected to be low. Therefore, some researchers have investigated the effects of cutting parameters on tool wear in turn-milling [12,13].

In this study, the major concern is to establish a comprehensive process model for orthogonal, tangential and co-axial turn-milling operations including chip thickness, kinematics, machined part quality and cutting forces. Therefore, for the first time in the literature uncut chip geometry and engagement limits are introduced at the outset for three types of turn-milling operation. Next, as an original contribution to the literature, cutting forces are evaluated by using uncut chip geometry and orthogonal cutting data. Moreover, the surface roughness is formulated for circumferential and axial directions. In addition, material removal rate (MRR) is specified and optimized by taking into account tool wear and machined part quality. The models and results presented in this work are believed to help understanding of turn-milling process geometry and mechanics as well as selection of process parameters better in order to increase productivity and part quality in these operations.

2. Uncut chip geometry

In order to understand the mechanics of turn-milling, firstly the chip formation is considered. Unlike conventional methods, in turn-milling chip removal is achieved by the combined rotations of both cutting tool and workpiece. As a result, there are practically two feed rates; circumferential feed and axial feed. Circumferential feed is defined as the tool rotational motion around the workpiece which is a result of the workpiece rotation. Axial feed, on the other hand, is the translation motion of the cutting tool along the workpiece. The combined motions of two feed rates result in a helical tool path as shown in Fig. 1.The parameters used to describe a turn-milling operation are summarized in Fig. 1 which illustrates depth of cut (a_p), feed per tooth (f_z), feed per workpiece revolution (a_e), eccentricity (e), number of tool revolutions (n_t), tool radius (R_t), workpiece radius (R_w) and number of workpiece revolution (n_w) and projected length of the tool onto workpiece (P_L). Fig. 1 also tells us that turn-milling can be defined by an analogy to conventional milling operation. If one assumes that the workpiece is stationary and the tool moves around it, the circumferential feed (f_z) corresponds to the feed rate in conventional milling where axial feed (a_e) defines the radial depth of cut.

2.1. Orthogonal turn-milling

In orthogonal turn-milling, the rotation axis of the cutting tool is perpendicular to the rotation axis of the workpiece [4]. The chip is formed by both the bottom and the side of the tool in orthogonal turn-milling [10] as can be seen in Fig. 2a. The uncut chip geometry (Fig. 2b) is a fundamental need in process modeling, and can be obtained by considering the initial and the final positions of the tool within one tool revolution.

Fig. 3 shows the cross-section of the uncut chip. Points 1, 2 and 2′ in Fig. 3 form envelop of the initial position of the cutting tool whereas points 1, 3 and 3′ form the final position of the cutting tool in one revolution of the tool. The uncut chip cross-section area in Fig. 3 can be divided into two segments: the first segment is the lower section of the chip cut by the tool bottom face, and the second one is the higher section removed by tool side edge. Uncut chip geometry can be defined by geometrical relations of the lines 1–2, 1–3, 2–3 and θ which is the angle between lines 1–2 and 1–3 representing the rotation of the tool around the workpiece in one revolution of the cutting tool.

Line 1–2 represents the bottom of the tool at the initial position and can be expressed by

$$z(x) = \tan\theta x + \frac{(R_w - a_p)}{\cos\theta} \quad (1)$$

where

$$\theta = \frac{2\pi}{mr_n} \quad (2)$$

where x is the position along the X-direction, m is the number of cutting teeth and r_n is the ratio of n_t/n_w. The bottom of the tool at the final position in Fig. 3 corresponds to the line 1–3 and can be determined by

$$z(x) = (R_w - a_p) \quad (3)$$

Arc 2′–3′ is on the surface of the workpiece

$$z(x) = \sqrt{(R_w^2 - x^2)} \quad (4)$$

As mentioned before, there are two different regions on the uncut chip geometry; the limits of these two regions are determined by the points 1, 2 and 3:

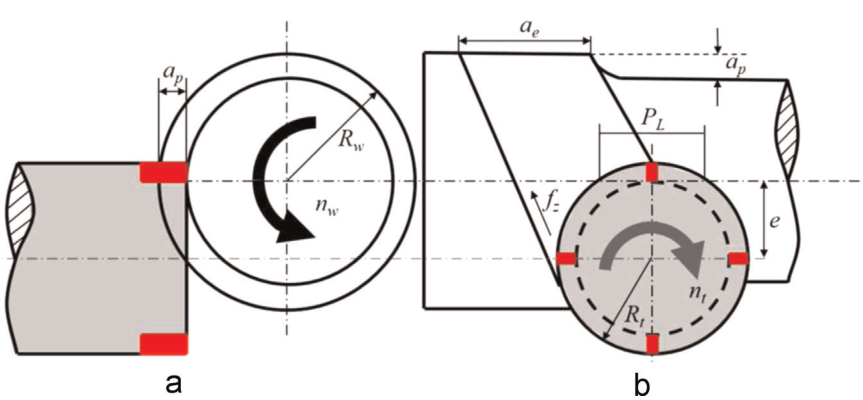

Fig. 1. Cutting geometry in turn-milling. (a) Side view of the process. (b) Top view of the process.