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Mechanics and dynamics of thread milling process

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ABSTRACT

This paper presents the mechanics and dynamics of thread milling operations. The tool follows a helical path around the wall of the pre-machined hole in thread milling, which has varying tool-part engagement and cut area during one threading cycle. The variation of cut area that reflects the kinematics of threading as well as structural vibrations is modeled along the helical, threading path. The mechanics of the process are first experimentally proven, followed by the formulation of dynamic thread milling which is periodic in threading cycle, in a semi-discrete time domain. The stability of the operation is predicted as a function of spindle speed, axial depth of cut, cutter path and tool geometry. The mechanics and stability models are experimentally proven in opening M16 × 2 threads with a five-fluted helical tool on a Steel AISI1045 workpiece.

1. Introduction

Threads are traditionally produced by tapping on machining or turning centers by keeping the feed per revolution directly equal to thread pitch at low spindle speeds. Moreover, tapping requires a dedicated tool with the same diameter as the hole to be threaded. An alternative is recently emerged thread milling, where the tool follows a combined helical–circular motion at high spindle speeds. The thread milling tool can machine threads on any hole which has a larger diameter than the cutter. This paper presents the predictive modeling of cutting forces and chatter-free cutting conditions for the optimal threading of holes without damaging the tool and threads.

A number of researchers have studied the tapping process in the past. Lorenz [1] investigated the effects of cutting speeds and tap geometries on torque using statistically designed experiments, and showed that the cutting speed and chamfer relief have significant influence on torque. Agapiou [2] pointed out that the effect of the speed on the steady state torque was not pronounced while the peak torque increased with speed. Dogra et al. [3], and Cao and Sutherland [4] developed mechanistic models to predict cutting forces in a general tapping process by using oblique cutting theory, and modeled the cutting force coefficients as functions of uncut chip thickness and cutting velocity. Dogra et al. [3] considered the effects of tool and hole geometry, material characteristics, process parameters and process faults, whereas Cao and Sutherland [4] predicted tapping torque and axial force under dry and wet tapping conditions. Mezentsev et al. [5] predicted thread height and pitch diameter mechanistically with the presence of tool axis misalignment and runout. Armarego and Chen [6] presented predictive modeling of torque and thrust force by considering tapping geometry, cutting speed and the workpiece material.

Lee and Nestler [7] and Fromentin and Poulachon [8] dealt with interference and the tooth profile of the thread milling cutter. Fromentin et al. [9] studied the relationship between different penetration strategies and the level of interference, and stated that a modified half revolution penetration strategy can reduce the interference and hence create more accurate thread. Sharma et al. [10] investigated the effect of milling cutter tool geometry and penetration strategies on cutting forces during thread milling. Fromentin and Poulachon [11,12] developed mathematical models to analyze the tool envelope profile, tool angles and uncut chip thickness. Araujo et al. [13,14] simplified the thread milling process as a common end milling operation by neglecting the motion in the *Z*-direction, and consequently expressed the cutting force coefficients as empirical functions of feed and spindle speed. Lee et al. [15] used the dual-mechanism cutting force model to predict the cutting forces for thread milling operations. Jun and Araujo [16,17] adopted the lumped-mechanism model to predict the thread milling force in a thrilling process, which can perform both drilling and thread milling with one tool. Araujo et al. [18] presented an experiment-based work with geometrical analysis to understand the effects of thread milling geometry, cutting conditions and tool angles on cutting forces for titanium alloy, and concluded that resultant forces can be reduced by optimizing flute angle.

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Nomenclature

a_p	axial depth of cut
b_{ij}	width of cut related to the disk element (j) of the flute (i) (see Fig. 5)
dz	relative axial position in one complete thread, which is defined by Eq. (4)
D	nominal diameter of the internal thread
D_1	minor diameter of the internal thread
D_m	maximum diameter of the thread mill
D_{1m}	minor diameter of the thread mill
f	feed rate [mm/tooth]
$F_{t,ij}(t), F_{r,ij}(t), F_{a,ij}(t)$	three orthogonal elemental cutting forces related to the disk element (j) of the flute (i) in cutting edge coordinate (RTA)
$F_{T,ij}(t), F_{R,ij}(t), F_{Z,ij}(t)$	tangential, radial forces and axial cutting forces related to the disk element (j) of the flute (i) (see Fig. 4(a))
F_{x_c}, F_{y_c}	total cutting forces in the directions of x_c and y_c of the rotating coordinate system $x_c y_c z_c$
$h_{ij}(t)$	equivalent uncut chip thickness related to the disk element (j) of the flute (i)
$h^c_{ij}(t)$	uncut chip thickness related to the disk element (j) of the flute (i), which is defined in the direction normal to the local cutting edge
l_e	axial length related to slope part of the thread (see Fig. 1)
M, **C** and **K**	lumped mass, damping and stiffness matrices of the tool-spindle system
N	Number of flutes
p	thread pitch length
S	spindle speed [rev/min]
t	time
T	spindle period of the cutter [s]
$x_c y_c z_c$	rotating coordinate system on the cutter, and the positive direction of y_c is always from the cutter's center to the hole's center (see Fig. 4(a))
XYZ	global Cartesian coordinate system (see Fig. 4(a))
z_{ij}	axial length related to the disk element (j) of the flute (i) (see Fig. 5)
$z(i,j)$	z coordinate of the disk element (j) of the flute (i) in local coordinate system $x_c y_c z_c$
α	thread angle
$\alpha_{n,ij}$	normal rake angle related to the disk element (j) of the flute (i)
α_r	radial rake angle on the maximum diameter of the mill
β	helix angle on the maximum diameter of the mill
β_a	average friction angle on the rake face
η_f	inclination of the feed direction in the unrolled plane (see Fig. 5)
η_{ij}	chip flow angle related to the disk element (j) of the flute (i)
$\theta_{en,ij}(t), \theta_{ex,ij}(t)$	entry and exit angles related to the disk element (j) of the flute (i) (see Fig. 4(b))
$\theta_{ij}(t)$	instantaneous radial immersion angle related to the disk element (j) of the flute (i) (see Fig. 4(a))
κ_{ij}	tool cutting edge angle of the disk element (j) of the flute (i)
$\boldsymbol{\xi}, \boldsymbol{\omega}$	diagonal damping ratio and natural frequency matrices of the tool-spindle system
ρ and λ	cutter axis offset and its location angle
τ	tooth passing period and $\tau = T/N$
τ_s	shear stress at the shear plane
$\varphi(t)$	reference angle of the tool center with respect to the origin of the global coordinate system XYZ
ϕ_n, β_n	normal shear and friction angles in oblique cutting
ψ_{ij}	local inclination angle related to the disk element (j) of the flute (i)
Ω	angular velocity of the tool [rad/s]
ω	angular traverse speed of the tool along the tool path [rad/s]
$\vartheta_1(t)$	angular position of the cutter center related to path 1 (see Fig. 2)
$\vartheta_2(t)+\pi$	angular position of the cutter center related to path 2 (see Fig. 2)

Although the chatter stability of conventional metal cutting operations such as turning, boring, drilling and milling, have been studied in the past, the stability of thread milling, which is the core focus of this paper, has not been studied before. The stability of conventional milling has been solved either in frequency domain as presented by Budak and Altintas [19], or in semi-discrete time domain as presented by Insperger and Stepan [20] and in the time finite model proposed by Bayly et al. [21]. The frequency domain methods tend to average time varying directional factors by taking either their averages [19] or a few harmonics [22]. Eksioglu et al. [23] and Wan et al. [24] studied the stability of the complex milling cutters in semi-discrete time domain. Kardes and Altintas [25] developed frequency domain and time finite element models to study the dynamics of the circular milling process, which has a similar tool path to thread milling. Li et al. [26] applied the frequency domain method to predict stability lobe diagram in helical milling process of holes. However, the thread milling process has varying engagement, chip generation and directional factors within one cycle of the thread milling operation, and its stability has not been reported in the literature.

This paper presents the modeling of thread milling stability in semi-discrete time domain. First, the generation of static uncut chip thickness is presented in Section 2 by considering the geometry of threading mill shown in Fig. 1, thread and hole geometries, varying tool-workpiece engagement conditions and cutting forces. The influence of lateral vibrations of the tool on the uncut chip thickness is modeled in Section 3. The stability of the thread milling process is modeled and predicted by transforming the dynamic cutting process into semi-discrete time domain. The proposed models are experimentally validated in Section 4, and the paper is concluded in Section 5.

2. Mechanics of the thread milling process

The thread milling cutter follows a helical path with both circular and vertical feed motions as shown in Fig. 2. The threading cycle is described as follows [9,10]:

i. Position the tool at the center of the pre-drilled hole, and lower it to the level of the threading position.
ii. Engage into the workpiece along the half helical tool path 1. As shown in Fig. 3, the hatched region related to arc $P_1P_2P_3$ represents the area of cut after tool path 1.
iii. Follow helical path 2 to move one complete revolution around the hole in planetary motion and simultaneously move up with a helical interpolation which has a thread pitch (p). Fig. 3 shows the area of cut during path 2, which overlaps partially