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Mechanics of tapping process with emphasis on measurement of feed error and estimation of its induced indentation forces

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ABSTRACT

Feed error induced by the mismatch between the spindle motor and Z-axis motor of the machine can significantly influence the cutting loads during thread tapping process. In this paper, a comprehensive study, which allows predicting the feed error-induced force together with measuring the actual tapping feed error, is presented by establishing simplified methods. Convenient experimental setup and procedure are first proposed to measure the actual feed error by using a laser tachometer along with a laser interferometer, followed by modeling the contact status between the tap flank and workpiece under feed error as an indentation effect, under which the corresponding indentation force is derived as a simplified proportional function of the indentation volume by using the basic principle of contact mechanics. Identification scheme is also developed to determine the proportional coefficient, i.e. the indentation force coefficient. Total tapping forces are obtained by summing cutting forces related to material removal mechanism and the indentation forces associated with feed error. Experimental verifications have been carried out to validate the proposed methods.

1. Introduction

Tapping, which is conducted on machining or turning centers by keeping the feed per rotation equal to thread pitch, is one of the widely used processes for manufacturing internal threads. Although other thread making operations such as thread milling and turning have made great successes in the last decades [1–6], tapping is almost the only way to manufacture internal thread for holes with small diameter. Due to the characteristic of simultaneous engagement of all flutes and axial indentation effect under feed error, such an operation is often accompanied by relatively excessive load, which leads to breakage of tap tooth and further ruin the parts being machined. However, as reported, tapping operation is still amongst the most complex and least understood processes in practice [7], and available works on studying the mechanism of tapping process are very limited. This paper presents the mechanics of making internal thread with tap.

The early researches on tapping mechanics date back to 1950s. Johnson [8] conducted some experimental study on tapping process, and concluded that compensation for the pull of the tap was needed to obtain a good thread profile in 1951. Later, Doyle and Dean [9] pointed out that the axial forces on tap, which may be produced by cutting action, the operator or the machine, can prevent tap from advancing at the correct rate and cause excess cutting of the grooves by tap teeth's flanks. Henderer [10] adopted orthogonal cutting assumption and shear plane model to investigate the mechanics of tapping process. Armarego and Chen [7] modeled torque and thrust force as functions of cutting speed, tooth number and tap geometry. Based on Armarego's approach [7], Chen and Smith [11] studied the geometry and specification of straight flute taps and developed a computer-aided predictive models of side force, thrust force and torque. Dogra et al. [12] and Cao and Sutherland [13] predicted the tapping torque and thrust force using mechanistic model. Process faults and hole geometry were considered to analyze the chip load by Dogra et al. [12], while dry and wet cutting conditions were separately taken into account to determine the cutting force coefficients by Cao and Sutherland [13]. As reported in Ref. [14], Dogra's model [12] is incapable of dealing with tooth breakage and the presence of multiple faults cases, and to overcome this drawback, a model-based method for tapping fault detection was proposed by Mezentsev et al. [14].

Some experimental studies have also been conducted to explore the influences of the concerned factors on tapping torque and friction. Lorenz [15] conducted statistically designed experiments to investigate the effects of cutting speed, thread relief, chamfer relief and rake angle on torque, and found that the higher order interactions of the variables, in particular those of speed and chamfer relief, significantly affect the torque. Agapiou [16] studied the high speed tapping performance of both roll form tap and cut tap, and found that the design of the roll form tap significantly affected their torque, while the torque for

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Nomenclature

$a_{e,ij}(t)$	radial depth of cut related to the jth disk element of the ith tooth at t
D_{min}	minor diameter of internal thread
D_{nom}	nominal diameter of internal thread
D_{max}	maximum diameter of internal thread
d_z	the discrete length along Z-axis
E and v	Young's modulus and the Poisson ratio of workpiece material
$F_{T,ij}(t)$, $F_{R,ij}(t)$ and $F_{A,ij}(t)$	the tangential, radial and axial cutting force related to the jth axial disk element of the ith tooth at t
$\mathbf{F}_I(t)$	indentation force due to feed error
$\mathbf{F}_c(t)$	cutting force due to material removing
$h_{ij}(t)$	instantaneous uncut chip thickness related to the jth axial disk element of the ith tooth at cutting instant time t
i, j and k	index numbers of the tooth, axial disk element and tooth thread
K_T, K_R and K_A	shearing force coefficients in tangential, radial and axial directions
K_p	indentation force coefficients
$l_{w,ik}$	tooth land width related to the kth thread of the ith tooth
N_t	number of tap teeth
N_{thr}	number of tap threads
P	thread pitch
P_0	the amplitude of contact stress
R_h	radius of the pre-drilled pilot hole
R_{ik}	radius of the kth thread of the ith tooth
$r_{0,i}$	minimum radius of the bottom of the ith tooth
S_{ind}	contact area between the tap land and the workpiece
t	cutting instant time
T	spindle rotation period
u_{p,B_1}	indentation force-induced displacement of point B_1
$v_f(t)$	feed velocity corresponding to t
V_{ind} and $V_{ind,ik}$	total indentation volume and indentation volume induced by ith tooth kth thread, respectively
$x_I(t)$	displacement of the tap corresponding to t
α	thread angle
α_n, β and γ_n	normal rake angle and helix angle of tap's cutting edge, and clearance angle of cutter
β_n and η	friction angle and chip flow angle
δ	feed error, mm/rev
$\delta_{p,ik}$	maximum indentation height related to the kth thread of the ith tooth
$\theta_{i,j}(t)$	instantaneous radial immersion angle related to the jth axial disk element of the ith tooth at t
κ_c	chamfer angle of the tap's cutting part
κ_{ij}	cutting edge angle of the jth disk element of the ith tooth
λ	thread lead angle
τ_s	shear stress of the workpiece materials
ψ_n	shear angle defined as the angle between the shear plane and the cutting speed

different cut tap designs was similar and usually lower than that for roll tap. Cao and Sutherland [13] found that the lubricating conditions greatly influence the friction coefficient between tap and workpiece materials, and indicated that the coefficient for dry sliding is about four times of that with cutting fluid lubrication. Bhowmick et al. [17] experimentally studied the tapping process of Al–Si alloys with minimum quantity lubrication (MQL), and observed that the presence of sulfur and phosphorus-based additives in the MQL fluids can help prevent aluminum adhesion. Saito et al. [18] experimentally studied the effect of friction at chip–tool interface on chip geometry and chip snarling in tapping process, and stated that plowing friction due to the abrasive particles on the tap increased the friction coefficient at the rake face–chip interface, resulting in the decrease of the chip curl diameter and prevention of chip snarling.

It should be highlighted that the feed error due to the mismatch between the spindle speed and Z-axis feed has great influence on tapping load, and the work stated above did not include this aspect. There are limited researches that have been carried out to study this [19–21]. Ahn et al. [19] found that feed error varies as feed forward gain and cutting speed change, and can lead to the increase of tapping trust and damage of threads during retreating. However, they did not establish the relationship between the feed error and the additional thrust, i.e. indentation force. Futami and Nakamura [21] studied the feed error control method in high-speed NC tapping, and achieved the precision of 10 μm by their algorithm. Dogra et al. [20] derived an integration expression to calculate the feed error-induced indentation force by artificially assuming that the contact stress between the tap flank and the workpiece has a distribution form of second order polynomials, in which one polynomial coefficient is needed to be re-determined once feed error changes. At the same time, the feed error was obtained by artificially setting mismatched feed rates rather than by measuring the actual feed error in tapping process. Actually, artificial setting is based on the premise that there is no feed error if the feed per rotation is set to be equal to thread pitch. The actual mismatch between the spindle motor and Z-axis motor of the machine itself was ignored in their work.

Hence, this paper presents a comprehensive study that allows the identification of the actual feed error induced by the servo system of the machine, which is then used to formulate the expression of its indentation force. The effort for experimentally determining the actual feed error and establishing simplified indentation force model is the main contribution of this paper. First, convenient experimental setup and procedure are proposed to measure the actual feed error rather than artificially setting, as detailed in Section 2. Second, the indentation force is theoretically derived in Section 3 to be a relatively simplified proportional function of the indentation volume between the flank of the tap and the workpiece, and proportional coefficient K_p is independent of feed error and tap geometry. This characteristic makes it convenient to predict the tapping force with various feed

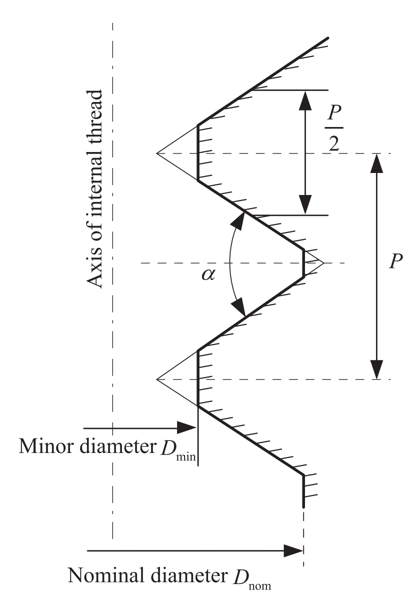

Fig. 1. Basic profile of internal thread.