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Time domain prediction of milling stability according to cross edge radiuses and flank edge profiles

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ABSTRACT

This article proposes a time domain model for predicting an end milling stability considering process damping caused by a variety of cross edge radiuses and flank profiles. The time domain model of calculating indentation areas, as well as regenerative dynamic uncut chips, is formulated for the prediction of the stabilizing effect induced by interference areas between the edge profiles and undulation left on a workpiece. The interference area generates forces against the vibration motion, which acts as a damping effect. In the model, the present and previous angular position of cross radiuses and flank edge profiles are located to calculate the dynamic uncut chip as well as indentation area based on a time history of the dynamic cutter center position. The phenomenon that chatter is damped according to cross edge radiuses and flank edge profiles is successfully simulated with the proposed dynamic model and validated through the extensive experimental tests.

1. Introduction

Machining chatter often turns a great deterrent against high productivity and machining quality. There have been extensive research works on the mechanics and dynamics of milling processes. Tobias and Tlusty introduced first chatter stability laws in the frequency domain [1,2]. Sridhar presented the time domain solution with two coupled, delayed differential equations with time-varying coefficients [3]. Minis and Yanushevsky proposed the first analytical solution of the milling stability using Floquet's theory by advancing from Sridhar's formulation [4]. Altintas and Budak developed a general and closed solution of the milling stability in the frequency domain [5,6]. Some articles proposed added stability lobes to simulate the low radial immersion cutting during high speed machining [7,8]. Olgac et. al. included both single and multiple time delays and validated their stability law on uniform and variable pitch cutter results. [9] Ko and Altintas proposed mechanistic and dynamic models in time and frequency domain for plunge milling processes [10,11]. The developed stability model can predict a torsional–axial vibration as well as lateral vibrations. Eksioglu and Altintas [12] proposed a general formulation of flexible mills and workpiece at high axial and small radial depths of cuts. Recently, modeling of milling process damping has been improved by a few researchers [13–16]. Tunc and Budak [15,16] proposed an indentation model based on the existence of a separation point on the cutting edge in order to estimate process stability. Eyniyan and Altintas [17,18] proposed a dynamic cutting force model and a novel experimental technique for the identification of dynamic coefficients with a piezo actuator set-up. Researchers mentioned that the interaction between a wavy surface and a cutter flank should be further investigated as it affects the process damping.

Regarding the edge radius effect, Waldorf et al. [19] proposed two ploughing models for static/orthogonal model and Endres [20] worked on the force balance under the deformation zone for static force prediction. Albrecht [21] investigated that the existence of hone radius causes the workpiece material to be extruded against the cutting tool, which increases process damping. Wu [22] investigated the relation of the penetration depth to the uncut chip thickness, vibration amplitude and the instantaneous shear angle. Shawky and Elbestawi [23] estimated the depth of penetration due to cross edge radius and Ranganath et al. [24] estimated the separation angle in order to incorporate indentation forces into the overall force model.

Depending on tool wear or tool edge preparation, the profiles of the cross edge and its adjacent flank edge vary which affects the surface quality as well as stability significantly. Fig. 1 shows the examples of different cross edge radiuses according to insert or solid type of end mills. So, it is important to consider the cutting edge radiuses of the tool as one of the variables for predicting machining stability. In addition, the profile of flank edge adjacent

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Nomenclature

α	radial rake angle of cutting edge
β	cutting edge angle
θ_h	helix angle
δ_f	flank elemental edge angle
L_f	flank elemental length
φ_p	pitch angle
$F_n(i, j, k)$	normal pressure force
$F_f(i, j, k)$	frictional force
$\vec{\tau}$	unit vector tangent to the cutter edge
$\vec{n}$	unit vector normal to rake face
$\vec{b}$	unit vector on the rake surface and perpendicular to the cutter edge
$\vec{T_c}$	chip flow vector
N_f	the number of flutes
Δa	length of edge element along the radial direction.
N_a	total disk number
θ	rotation angle of the cutter
φ_e	cutting edge location angle
$T(\varphi)$	transformation matrix
φ_c	flute spacing angle
h_c	uncut chip thickness
h_{cr}	rescaled uncut chip thickness
ds	incremental cutting edge length
K_n	normal cutting force coefficients
K_f	frictional cutting force coefficients
θ_c	chip flow angle
R_r	radial runout
R	cutter radius
e_r	cross edge radius
e_{ra}	separation angle
r_k	cutting edge position from cutter center

to cross edge may change according to tool wear, which need to be measured and modeled to simulate its damping effect accurately.

This paper proposes a fast and comprehensive time domain model which simulates a dynamic uncut chip as well as the interaction of cross–flank edge profiles with the undulation of machined surface. It can predict how the edge profiles affect the milling stability by tracking the interaction between cross–flank edge profiles and undulation. Contact forces between cross–flank edges and wave on the machined surface contribute to the dynamics of the cutting process by increasing the overall damping. The elemental contact forces are integrated by simulating time-dependent elemental indentation volume between cross–flank edge and undulation profiles, which act against the cutting forces of removing the dynamic uncut chip. By tracking dynamic cutter center positions determined by vibration, runout, and feed motions, the time-dependent angular positions of the edge profiles as well as the undulation can be rapidly and precisely located. The angular positions are used to simulate the dynamic uncut chip as well as the contact area of cross–flank edge profiles against the undulation left on the machined surface. According to a variety of edge radiuses and flank profiles, the milling stabilities are experimentally compared and analyzed. The corresponding simulation results are presented and validated with the experimental ones on the damping effect with cross edge radiuses and flank edge profiles.

2. Time domain milling model considering cross–flank edge profiles

Fig. 2 illustrates the proposed time domain solution process. Firstly, after the cross edge radius and flank edge profiles are measured, tool geometry information, modal parameters, cutting conditions, and workpiece info are input to the simulation model. The edge profiles are digitized to simulate elemental forces and dynamic uncut chip thickness. After solving the dynamic equation using a numerical time integral scheme, the cutter center positions at present and previous rotations are updated. By extracting the

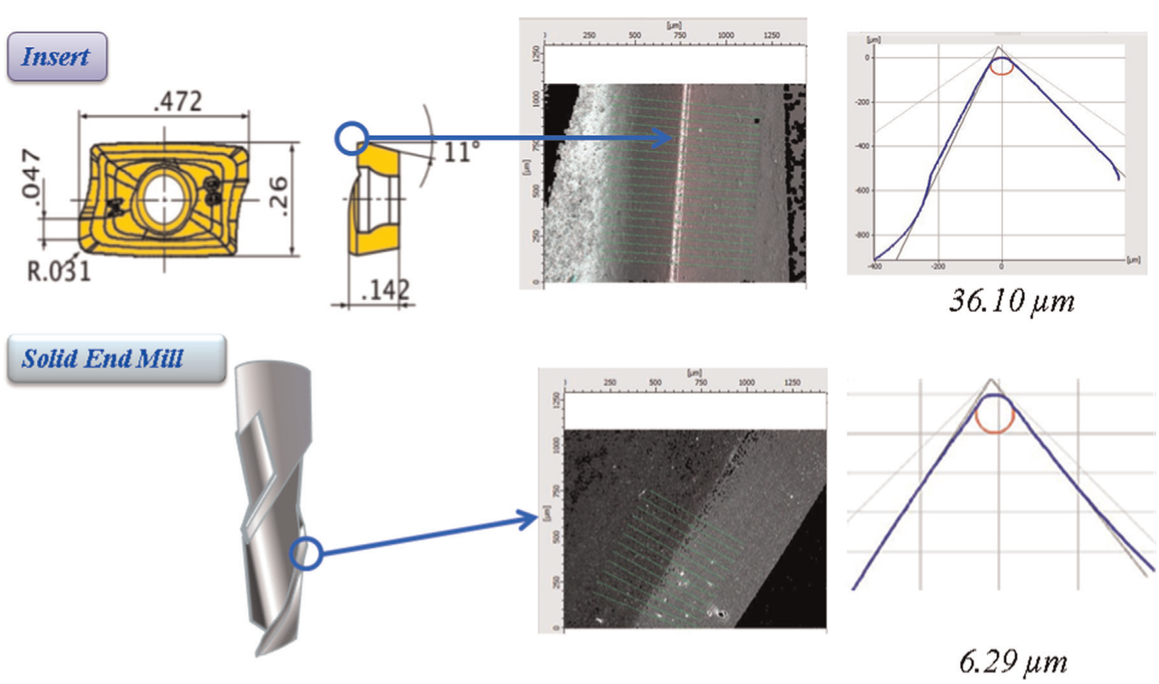

Fig. 1. Cross edge measurement according to the type of cutting edge.