Journal of Materials Processing Technology 209 (2009) 5766–5776

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Chatter suppression in micro end milling with process damping

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ARTICLE INFO

Article history:
Received 2 February 2009
Received in revised form 14 June 2009
Accepted 15 June 2009

Keywords:
Chatter
Micro milling
Process damping
Receptance coupling

ABSTRACT

Micro milling utilizes miniature micro end mills to fabricate complexly sculpted shapes at high rotational speeds. One of the challenges in micro machining is regenerative chatter, which is an unstable vibration that can cause severe tool wear and breakage, especially in the micro scale. In order to predict chatter stability, the tool tip dynamics and cutting coefficients are required. However, in micro milling, the elasto-plastic nature of micro machining operations results in large process damping in the machining process, which affects the chatter. We have used the equivalent volume interface between the tool and the workpiece to determine the process damping parameter. Furthermore, the accurate measurement of the tool tip dynamics is not possible through direct impact hammer testing. The dynamics at the tool tip is indirectly obtained by employing the receptance coupling method, and the mechanistic cutting coefficients are obtained from experimental cutting tests. Chatter stability experiments have been performed to examine the proposed chatter stability model in micro milling.

1. Introduction

Micro milling operations can be used to manufacture complex 3D miniature components from a variety of engineering materials, especially engineering alloys. The micro milling process is similar to the macro operation, where the spindle rotates an end mill (miniature end mill in micro milling) to remove a portion of the workpiece; and, as with macro machining operations, micro machining processes also exhibit an unstable phenomenon called regenerative chatter (Mascardelli et al., 2008; Altintas and Budak, 1995), due to changes in the chip thickness. Chatter can cause serious damage in the micro scale, since the tolerances are generally tight and small vibrations can break the tool and ruin the part. Due to fragile nature of micro tools, a small chip thickness is used to remove a portion of the workpiece, in order to minimize excessive loads and prevent tool breakage and large deflections.

Micro machining phenomena differ from macro machining due to size effects, which occur because the edge radius of micro tools is comparable to the uncut chip thickness, resulting in large negative rake angles (Vogler et al., 2003). This is particularly evident at low feed rates, where the effects of plowing are more significant (Malekian et al., 2009). Process damping can increase stability, especially at low spindle speeds (Tobias and Fishwick, 1958; Kegg, 1969; Tlusty, 1993). Elastic recovery increases the friction between the flank face of the tool and the workpiece and amplifies the effect of process damping. Haung and Junz Wang (2007) assumed that cutting forces (including process damping) contribute to two physical mechanisms—chip shearing and plowing, where the shearing force is proportional to the chip thickness and the plowing force is proportional to the contact length between the cutting edge and the machined surface. Chiou et al. (1995) presented a model for chatter stability for turning that considered the effect of tool wear. In their model, the process damping force due to tool wear was assumed to be proportional to the volume of the deformed workpiece material under the clearance face of the tool.

The objectives of this paper are the examination of micro end milling processes with process damping and the formulation of the chatter stability method. We have extended Tlusty's (2000) conventional chatter theorem by incorporating process damping, which is a function of the interference volume between the tool and the workpiece (Wu and Liu, 1985).

In order to accurately predict chatter stability, the accurate measurement of tool tip dynamics and the cutting coefficients are also needed. Since experimental impact hammer tests cannot be performed on fragile tool tips, we have utilized the receptance coupling method (Park et al., 2003; Schmitz et al., 2002) to indirectly couple the machine tool dynamics with arbitrary tool dynamics to identify the tool tip dynamics. This involves the mathematical coupling of the experimental frequency response functions and the dynamics acquired using the finite element analysis method. Furthermore, the mechanistic cutting force model is utilized to obtain the cutting coefficients. Experimental tests have been performed to compare the simulated chatter stability results.

The paper is organized by presenting, in Section 2, the dynamic model of micro end milling with process damping and the derivation of the process damping coefficient, which is based

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doi:10.1016/j.jmatprotec.2009.06.009

Nomenclature

$\dot{r}$	tool radial velocity (m/s)
$\bar{\Phi}_c$	mean of the oriented cutting transfer function (m/N)
$\bar{\Phi}_{pd}$	mean of the oriented process damping transfer function (m/N)
$\dot{x}$, $\dot{y}$	tool velocity in X and Y directions (m/s)
a	axial depth of cut (m)
a_0	nominal axial depth of cut (m)
a_{lim}	critical depth of cut (m)
b_{mf}	rotational dynamics, (θ/force)
b_{mm}	rotational dynamics, (θ/moment)
c	feed rate (m/flute)
C_x, C_y	system's damping in X and Y directions (N/ms)
e	error between the experimental and analytical instantaneous forces
F_c	shearing cutting force (N)
F_{exp}	experimental force (N)
f_i	force component in the experimental modal analysis
F_p	plowing force (N)
F_{pd}	process damping force (N)
$F_{pd,r}$	radial process damping force (N)
$F_{pd,t}$	tangential process damping force (N)
F_{theo}	theoretical force (N)
F_x, F_y	resultant forces in X and Y directions (N)
G_c	real component of the mean of the cutting oriented transfer function (m/N)
G_{ij}	assembled dynamics of the system
G_{pd}	real component of the mean of the process damping oriented transfer function (m/N)
h	chip thickness (m)
h_0	nominal chip thickness (m)
H_c	imaginary component of the mean of the cutting oriented transfer function (m/N)
h_{ij}	components of substructure dynamics (H_{ij})
H_{pd}	imaginary component of the mean of the process damping oriented transfer function (s^2/Kg)
K_p	plowing force coefficient
K_{pd}	process damping coefficient (N)
K_{pdr}	radial process damping force coefficient (N/m)
K_r	ratio of radial to tangential cutting
K_{re}	radial edge coefficient (N/m)
K_s	resultant cutting coefficient (N/m^2)
K_{tc}	tangential cutting force coefficient (N/m^2)
K_{te}	tangential edge coefficient (N/m)
K_x, K_y	system's stiffness in X and Y directions (N/m)
M_x, M_y	system's modal mass in X and Y directions (Kg)
r	tool radial displacement (m)
R	tool radius (m)
r_e	tool edge radius (m)
s	displacement along surface (m)
s_l	surface slope
T	period of spindle rotation (s)
V_p	plowed volume (m^3)
Δx, Δy	tool tip displacement in X and Y directions in subsequent passes (m)
Φ_c	cutting oriented transfer function (m/N)
Φ_{pd}	process damping oriented transfer function (m/N)
Φ_{xx}, Φ_{yy}	direct transfer functions in X and Y directions (m/N)
Φ_{xy}, Φ_{yx}	cross transfer functions (m/N)
α_p	effective rake angle (rad)
α_s	surface slope angle (rad)
β_f	angle of resultant process damping force with the radial direction (rad)
ϕ	immersion angle (rad)
μ_f	friction coefficient
θ	angle of resultant cutting force with the radial direction (rad)
ω_c	chatter frequency (rad/s)
$\omega_{n,i}$	natural frequency of the system for the ith mode (rad/s)
$\omega_{spindle}$	spindle speed (rad/s)
ψ_e	clearance angle (rad)
ζ_i	damping ratio of the system for the ith mode

on geometric and experimental measurements. The experimental setup is described in Section 3. In Section 4, there is a discussion on the dynamics of the tool tip, which has been obtained by implementing the receptance coupling method that combines the experimentally acquired dynamics with the finite element dynamics for micro tools, and the mechanistic cutting force model coefficients, which have been identified with a series of experimental cutting tests. The simulated results with process damping are compared with the results from the experimental chatter tests and the conclusions are presented in Sections 5 and 6, respectively.

2. Micro milling chatter

The dynamic model of micro end milling process is presented with process damping effects. The approach considers the process damping force to be proportional to the volume of elastically deformed material under the tool tip (Wu and Liu, 1985; Chiou et al., 1995). The stability model used in this study is based on Tlusty (1978), Tobias and Fishwick (1958) and Optiz (1969) models, in order to develop a pseudo single-degree-of-freedom (SDOF) system based on the oriented transfer functions.

2.1. Micro milling stability model

In order to perform a stability analysis of micro milling processes, the forces that act on the tool need to be investigated. Since the depth of cut is very small in micro machining operations, the influence of the helix angle on the planar forces is negligible and we have assumed the axial dynamics to have negligible effects. The equation of motions of the micro end milling process is described as a two-degrees-of-freedom (2DOF) system:

$$M_x\ddot{x} + C_x\dot{x} + K_x x = \sum_{i=1}^{N} F_{x,i} \tag{1}$$

$$M_y\ddot{y} + C_y\dot{y} + K_y y = \sum_{i=1}^{N} F_{y,i} \tag{2}$$

where M_x, M_y, C_x, C_y, K_x, K_y, F_x and F_y are the effective masses, damping ratios, stiffness and cutting forces in the X and Y directions, respectively.

Schematics of micro milling are depicted in Fig. 1. The machining force consists of two components, the cutting (F_c) and process damping (F_{pd}) forces (Tobias and Fishwick, 1958):

$$F = F_c + F_{pd} \tag{3}$$