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Analytical modeling and experimental validation of micro end-milling cutting forces considering edge radius and material strengthening effects

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ABSTRACT

This paper presents a novel micro end-milling cutting forces prediction methodology including the edge radius, material strengthening, varying sliding friction coefficient and run-out together. A new iterative algorithm is proposed to evaluate the effective rake angle, shear angle and friction angle, which takes into account the effects of edge radius as well as varying sliding friction coefficient. A modified Johnson–Cook constitutive model is introduced to estimate the shear flow stress. This model considers not only the strain-hardening, strain-rate and temperature but also the material strengthening. Furthermore, a generalized algorithm is presented to calculate uncut chip thickness considering run-out. The cutting forces model is calibrated and validated by NAK80 steel, and the relevant micro slot end-milling experiments are carried out on a 3-axis ultra-precision micro-milling machine. The comparison of the predicted and measured cutting forces shows that the proposed model can provide very accurate predicted results. Finally, the effects of material strengthening, edge radius and cutting speed on the cutting forces are investigated by the proposed model and some conclusions are given as follows: (1) the material strengthening behavior has significant effect on micro end-milling process at the micron level. (2) Cutting forces predicted increase with the increase of edge radius. (3) Considering varying sliding friction coefficient can enhance the sensitivity of the predicted cutting forces to cutting speed.

1. Introduction

In recent years, demands of micro products and components are growing in the fields such as electronics optics, aerospace and biotechnology. The miniature components usually have complex millimeter-level three-dimension geometries which require micron level accuracy. As an effective way to produce micro products, the micro end-milling can create more complex three-dimension geometries in a wide range of workpiece materials compared with the conventional fabrication methods such as photolithography and laser beam etching. Therefore, understanding and modeling of the micro end-milling process is desirable.

It is reported [1–7, 9–13] that in micromachining process, the specific cutting energy for removing unit volume of material increases nonlinearly with the chip thickness decreasing from a few hundred microns to a few microns. In early years, many researchers have attempted to explain and predict this scaling phenomenon. Most of studies attribute it to the edge radius effect [1–7]. Waldorf et al. [1] proposed a slip-line model to predict the plowing component of cutting forces caused by the edge radius, and a series of experiments were performed on 6061-T6 aluminum using tools with different edge radius. Vogler et al. [2] presented a new cutting forces prediction model for micro end-milling based on the slip-line model which considering the minimum chip thickness and material microstructure, and the microstructure level finite element simulations were performed to determine the model parameters. Woon et al. [3] investigated the effects of tool edge radius on the frictional contact and flow stagnation phenomenon with the finite element approach. Bissacco et al. [4] presented a theoretical model for cutting forces prediction in micro end-milling based on the oblique cutting model which including the uncut chip thickness to edge radius ratio, and the shearing and plowing force coefficients were determined by the orthogonal cutting experiments. Fang [5]

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Nomenclature

A, B, C, m, n coefficients of Johnson–Cook model
b magnitude of the Burgers vector (nm)
C_1, C_2 constant
C_p specific heat (J/kg K)
d_a axial depth of cut (μm)
$F_{x(amp)}, F_{y(amp)}$ cutting forces amplitudes in X- and Y-direction (N)
f_t feed per tooth (μm/tooth)
G shear modulus (GPa)
h uncut chip thickness (μm)
h_0 primary shear zone thickness (μm)
i inclination angle (°)
K number of flutes
K_{tc}, K_{rc}, K_{ac} shearing force coefficient in tangential, radial, axial direction (N/mm^2)
K_{te}, K_{re}, K_{ae} plowing force coefficient in tangential, radial, axial direction (N/mm^2)
K_0 preset value
L length of the primary shear zone (μm)
M Taylor factor
N rotation speed of the spindle (rpm)
R length variable in slip-line model [1]
r radius of the tool (mm)
re edge radius (μm)
$\bar{r}$ nye factor
T material temperature (°C)
T_m material melting temperature (°C)
T_r room temperature (°C)
u exponential factor
V cutting speed (m/min)
α nominal rake angle (°)
α_e effective rake angle (°)
α_n normal rake angle (°)
α_t empirical coefficient
α_r angle between feed rate and Y-direction (°)
β_n normal friction angle (°)
β_T percentage of the total shear deformation energy
γ run-out angle (°)
δ engagement angle (°)
ε equivalent plastic strain
$\dot{\varepsilon}$ equivalent plastic strain rate (s^{-1})
$\dot{\varepsilon}_0$ reference plastic strain rate (s^{-1})
ς constant
η strain gradient (μm)
$\eta_0, \gamma_0, \alpha_0, \rho_0$ angle variables in slip-line model [1]
η_c chip velocity angle (°)
θ angular position of cutter (°)
θ_f separation angle (°)
θ_s, θ_e Integrating start angle and integrating end angle (°)
λ helix angle (°)
μ sliding friction coefficient
ξ exponential constant
ρ radial run-out length (μm)
ρ_m material density (kg/m^3)
τ shear flow stress (MPa)
ϕ_n normal shear angle (°)

proposed a generalized slip-line model with a round edge tool to predict the shearing and plowing forces. Jin et al. [6,7] presented a slip-line model for micro orthogonal cutting process considering the tool edge radius effect, and the Johnson–Cook constitutive model was adopted to estimate the shear flow stress and hydrostatic pressure.

Material strengthening effect is one of the significant characteristics of the micro machining process. However, to date, very meager efforts have been dedicated to analytical modeling of cutting forces in micro end-milling process considering the effect of material strengthening. Dinesh et al. [8] linked the material strengthening behaviors observed in micro-/nano-indentation to that in micro machining and suggested that the material strengthening effect in micro machining could also be explained by the strain gradient plasticity theory. Based on the work in [8], Joshi et al. [9] presented a modified Johnson–Cook constitutive model by introducing the material length scale and effective strain gradient. Liu et al. [10] adopted this modified Johnson–Cook constitutive model to the finite element based micro orthogonal cutting simulations, and the results showed that the strain gradient strengthening effect is prominent especially at small uncut chip thickness. Lai et al. [11] also introduced this model to finite element simulations of micro orthogonal cutting. Rao and Srinivasa [12,13] developed a new strain gradient equation and introduced it to the modified Johnson–Cook constitutive model. The results showed that the predicted shear stress enhanced about three times compared to the model proposed by Joshi et al. [9] at uncut chip thickness of 10 μm.

The run-out have significant influence on the micro end-milling process. Some efforts have been devoted to modeling the effects. Bao et al. [14] proposed an analytical model to calculate the uncut chip thickness. Li et al. [15] developed a new uncut chip thickness computation algorithm for micro end-milling accounting for the combination of exact trochoidal trajectory of tool tip and run-out. The similar algorithms were adopted to calculate uncut chip thickness in [16,17]. Bissacco et al. [4] presented a simplified method to estimate the uncut chip thickness considering run-out and discussed the effect of run-out on cutting forces.

As mentioned above, a large number of models have been developed to predict the cutting forces in micro end-milling, but these models did not consider the effects of edge radius, material strengthening and run-out together, which could affect the prediction accuracy of the cutting forces. The objective of this paper is to develop a novel analytical micro end-milling cutting forces model by using the fundamental metal cutting principles and material physical properties, which incorporates the effects of edge radius, material strengthening, varying sliding friction coefficient and run-out. Development of such a new analytical model is contributed to further improve prediction accuracy for the cutting forces in micro end-milling. Besides, investigation of the effects of the material strengthening, edge radius and varying sliding friction coefficient affected by cutting speed on the cutting forces is also conductive to provide better understanding and monitoring for the micro end-milling process.

The organization of the paper is as follows: in Section 2, a novel analytical micro end-milling cutting forces model is developed which considers the edge radius, material strengthening, varying sliding friction coefficient and run-out. Section 3 presents the experimental set-up and compares the predicted results with the experimental measurements. In Section 4, the effects of the material strengthening, edge radius and cutting speed on the cutting forces are further investigated by using the proposed model. The modeling characteristics and some conclusions are given in Section 5.