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Mechanistic model for prediction of cutting forces in micro end-milling and experimental comparison

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ABSTRACT

Micro end milling is an important process in the manufacture of micro and meso scale products and has an advantage of creating more complex geometry in a wider variety of materials in comparison with other micro-machining methods. In this paper, a new methodology for predicting the cutting coefficients considering the edge radius and material strengthening effects is presented. Further a mechanistic model is developed to predict the cutting forces in micro end milling operation taking into account overlapping tooth engagements. The mechanistic model, derived from basics considering material property and principles of metal cutting, is valid for a wider range of cutting parameters. The model is validated with the results from micro slot end-milling of mild steel carried out on the basis of full factorial design. On comparing the amplitudes of cutting forces, it is seen that mechanistic model predicts the transverse force with an average absolute error of 12.29%, while a higher prediction error of 19.49% is obtained for feed force. Additionally the mechanistic model is able to predict the variations in the cutting forces with rotation of the cutter and average absolute deviations of 13% and 11% are obtained for feed and transverse forces, respectively.

1. Introduction

Micro machining processes are employed for the manufacture of miniature parts and devices having feature sizes that range from tens of micrometers to a few millimeters. Among the micro-machining processes, mechanical micro machining offers 3-D capability along with certain environmental benefits and has fewer limitations on materials [1,2]. The mechanical micro-machining uses physical cutting tools having geometrically defined cutting edges. Important applications are in the manufacture of micro parts for watches, micro scale fuel cells, housings for micro engines, micro scale pumps, medical devices, tooling inserts for fabrication of micro filters, packaging solutions for micro-optical and micro fluidics devices [3]. A better control that would allow the manufacturing industry to achieve higher productivity and quality at a lower cost is possible, only when accurate and reliable predictive models of the micro end milling process become available.

Micro end milling can be considered as a downscaled version of the conventional end milling process, involving the use of tools with diameters in the sub millimeter range (less than 0.5 mm) [4]. Besides downscaling of the process, there are specific issues related to micro end milling. As the tool diameter is small, higher spindle speed is required to achieve the recommended cutting speed and keep the reasonable level of productivity [5]. The ratio of feed per tooth to tool radius is much larger than macro end milling operation, due to which the stress variation on the tiny body of the micro tool is much higher. It leads to the deflection of the tool tip affecting the chip formation process, surface quality and thus shortens the tool life drastically [5–7]. The ratio of run-out to tool diameter is much larger in micro end milling, as the diameter of end mills itself is in the range of 100 to 500 μm [8]. Higher ratios of feed per tooth to tool radius, and tool run-out to tool diameter, along with unpredictable cutting action lead to rapid wear of the cutting tool and sudden tool failure [9]. Chip formation in micro milling is influenced by edge radius (typically 2 to 4 μm) of the cutter and its uniformity along the cutting edge length [10–14]. When the uncut chip thickness is comparable to the cutting edge radius, ploughing action is more dominant than cutting action [15,16]. This leads to the formation of burrs and side flow of the deformed material on the newly generated surfaces, thus increasing the surface roughness [17].

Following the studies on deformation mechanisms in orthogonal and oblique cutting [18,19], many researchers in the past have studied cutting mechanics in macro end milling process and influence of process parameters on the functional quality of the

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Nomenclature

r_e Radius of the cutting edge of the milling tool (mm)
r Radius of the cutter (*D*-diameter of cutter) (mm)
h Primary shear zone thickness (mm)
t_c Uncut chip thickness (mm)
θ_o Stagnation or neutral point angle (radian)
φ_n Normal shear angle (radian)
C_M Merchant empirical machining constant
β_n Normal friction angle (radian)
γ_n Normal rake angle (radian)
γ_{eff} Effective rake angle (radian)
θ Cutter rotation or immersion angle (radian)
f Feed in (mm/min)
f_x Feed in μm/tooth
N Spindle speed (rpm)
z Number of teeth on the milling cutter
dz Elemental width of cut (mm)
α Helix angle of the cutter (radian)
i Obliquity or inclination angle (radian)
η_c Chip velocity angle (radian)
γ_r Radial rake angle (radian)
δ Engagement or lag angle (radian)
θ_u Upper limit of angle (radian)
θ_l Lower limit of angle (radian)
d_a Axial depth of cut (mm)
F_t, F_r Tangential and radial cutting forces (N)
F_x, F_y, F_z Cutting force in feed, transverse and axial directions (N) (Subscript: *E*-Experimental, *M*-Mechanistic model)
$F_{x(amp)}$, $F_{y(amp)}$, $F_{z(amp)}$ Amplitude of cutting force in feed, transverse and axial directions (N) (Subscript: *E*-Experimental, *M*-Mechanistic model)
K_{tc}, K_{rc}, K_{ac} Cutting coefficient in tangential, radial and axial directions (N/mm^2)
K_{te}, K_{re}, K_{ae} Edge coefficient in tangential, radial and axial directions (N/mm)
σ Uniaxial flow stress (MPa)
τ Shear flow stress (MPa)
α_c Constant
G Shear modulus (MPa)
b Burgers vector magnitude (nm)
ρ_T Total dislocation density (mm^{-3})
ρ_s Density of statistically stored dislocations (mm^{-3})
ρ_g Density of geometrically necessary dislocations (mm^{-3})
η Effective strain gradient (mm^{-1})
l Intrinsic material length scale (μm)
σ_{Ref} Reference stress in the uniaxial tension (MPa)
V Cutting speed (mm/min)
ε Equivalent plastic strain
$\dot{\varepsilon}$ Equivalent plastic strain rate (s^{-1})
$\dot{\varepsilon}_o$ Reference plastic strain rate (s^{-1})
T Working or absolute temperature (°C)
T_{room} Room temperature (°C)
T_m Melting temperature of the work material (°C)
A Johnson–Cook material strength coefficient for yield strength (MPa)
B Johnson–Cook material strength coefficient for hardening modulus (MPa)
C Johnson–Cook material strength coefficient for strain rate sensitivity
n Johnson–Cook hardening coefficient
m Johnson–Cook thermal softening coefficient
t_{lim} Limiting value of uncut chip thickness, mm
K Proportion of the shear plane
τ_1 Shear yield strength of workpiece material along sticking region (MPa)
p_o Normal pressure at tool tip
ρ Exponential constant representing the pressure distribution
μ Sliding friction coefficient for the tool–workpiece combination

components [20–24]. Such studies in micro end milling started a decade back, and they rely strongly on the knowledge base available in the macro end milling domain [5,8,9]. Attempts are made to qualitatively explain the observed phenomenon such as material strengthening due to size effect and indicate the direction in which the cutting conditions should be changed to improve cutting performance.

Cutting forces are one of the most fundamental and important parameter in end milling operations. It can be seen from literature that researchers have used statistical methods and artificial intelligence techniques to predict the forces in end-milling operations. These models are valid within the experimental ranges of speed, feed and depth of cuts only. Not being satisfied with such statistical models which are derived from the experimental data itself, few attempts have been made to develop mechanistic model to predict cutting force from basic principles considering mechanical properties of materials and established principles of metal cutting. Development of mechanistic model is important to analyze the cutting process and get a clear understanding of the mechanism involved. In this paper, the cutting and edge force coefficients are established by a new approach and mechanistic model is developed to predict the cutting forces in micro end milling. The cutting forces predicted are verified by comparison with measured cutting forces obtained from the full factorial slot cutting end milling experiments on mild steel workpiece.

2. Mechanistic model

2.1. Cutting forces

End milling cutter has multiple cutting edges or flutes that are usually made helical to reduce the impact during the entry into the workpiece. A typical flat end milling cutter with two flutes is shown in Fig. 1. A cartesian coordinate system is defined with its origin located at the centre of the cutter in order to denote the cutting forces. The *X* axis is along the feed direction with respect to the workpiece, *Y* axis is transverse to the feed direction and *Z* axis is along the cutter axis. For modeling of the cutting force in end milling, it is a usual practice to divide the cutter into number of smaller elemental slices along the axis of the cutter and consider each element as oblique cutting edge with an inclination angle equal to the helix angle of the cutter [25]. In a unified approach, incremental force component in a given direction is considered to be influenced by two phenomena, namely cutting and rubbing/ploughing. The three incremental force components, namely tangential $dF_{tj}(\theta)$, radial $dF_{rj}(\theta)$ and axial $dF_{aj}(\theta)$ acting on