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Modeling of dynamic micro-milling cutting forces

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ABSTRACT

This paper investigates the mechanistic modeling of micro-milling forces, with consideration of the effects of ploughing, elastic recovery, run-out, and dynamics. A ploughing force model that takes the effect of elastic recovery into account is developed based on the interference volume between the tool and the workpiece. The elastic recovery is identified with experimental scratch tests using a conical indenter. The dynamics at the tool tip is indirectly identified by performing receptance coupling analysis through the mathematical coupling of the experimental dynamics with the analytical dynamics. The model is validated through micro end milling experiments for a wide range of cutting conditions.

1. Introduction

Highly accurate miniaturized components that are made up of a variety of engineering materials play key roles in the future development of a broad spectrum of products [1]. Many innovative products require higher functionality with significantly decreased size; however, conventional fabrication methods using photolithographic fabrication methods are not applicable to all engineering materials, and the processes are slow and expensive and limited to essentially planar geometries [2]. To overcome the challenges, micro-mechanical machining processes can be utilized to remove materials mechanically using a miniature tool to create complex three-dimensional shapes using a variety of engineering materials [3,4]. Micro-mechanical machining techniques bring many advantages to the fabrication of micro-sized features. They can produce micro-components cost-effectively because there is no need for expensive photolithographic masks. The flexibility and efficiency of micro-machining processes using miniature cutting tools allows for the economical fabrication of smaller batch sizes compared with other processes [5].

Due to the miniature nature of the mechanical removal process, micro-machining operations are susceptible to excessive tool wear, noise, and poor productivity. Thus, the modeling and understanding of micro-cutting processes are important to improve the machined part quality and increase productivity. However, the conventional mechanistic modeling approach cannot be applied to micro-scale cutting. In micro end milling, the cutting edge radius of the end mill is comparable in size to the chip thickness [6]. As a result, no chip is formed when the chip thickness is below the minimum chip thickness [7,8]; instead, part of the work material plastically deforms under the edge of the tool, and the rest elastically recovers. This change in the chip formation process, known as the minimum chip thickness effect and the associated material elastic recovery, causes increased cutting forces [9] and surface roughness [10] at low feed rates. Furthermore, when the chip actually forms during cutting with a finite edge radius tool, ploughing under the edge contributes to an increase in the specific energy, also known as size effect.

Many researchers have investigated the effect of ploughing on the size effect. Armarego and Brown [11] suggested that the greater relative contribution of the ploughing forces with a blunt tool is responsible for the increase in the specific cutting energy. Similarly, Lucca et al. [12] showed that the ploughing and elastic recovery, which were used to explain the increase in the cutting force, of the workpiece along the flank face of the tool play a significant role in micro-machining. Komanduri [13] studied the ploughing mechanism experimentally by using sharp tools with extremely negative rake angles to replace the rounded-edge tools.

In order to understand the ploughing mechanisms, ploughing force models have been developed by many researchers. Vogler et al. [9] made the first attempt at incorporating the effect of minimum chip thickness into a micro end milling force model. They used the slip-line plasticity model developed by Waldorf et al. [14]. More complicated slip-line plasticity models that account for elastic–plastic deformation and elastic recovery have

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Nomenclature

A_p	ploughed area (mm^2)
d_x, d_y	dynamic tool deflection (mm)
e	error
f_t	feed rate (mm/flute)
F_t	tangential force (N)
F_r	radial force (N)
F_{exp}	experimental force (N)
F_{theo}	theoretical force (N)
h	chip thickness (mm)
h_c	minimum chip thickness (mm)
h_{er}	height of elastic recovery (mm)
K_{rc}, K_{tc}	radial and tangential cutting coefficients (N/mm^2)
K_{re}, K_{te}	radial and tangential edge coefficients (N/mm)
K_{rp}, K_{tp}	radial and tangential ploughing coefficients (N/mm^3)
N	number of flutes
p_e	elastic recovery (%)
r_e	edge radius (mm)
r_0	tool run-out (mm)
V_p	ploughed volume (mm^3)
X_c, Y_c	location of the tool centre (mm)
G	receptance for the assembled structure (m/N)
H	receptance for substructures (m/N)
Δ	rpm of the spindle (rev/min)
θ	immersion angle (rad)
ψ_e	clearance angle (rad)
ψ_t, ψ_s	geometric angles (rad)

been developed by Jun et al. [15]. Fang [16] also developed a universal slip-line model for rounded-edge tools. The finite element model approach has also been utilized by many researchers to model the micro-cutting process and to understand size effect [17], machining stresses [18,19], and the influence of cutting edge radius on wear resistance [20]. However, the majority of these methods require many assumptions, and the parameters used in the model are difficult to estimate. There are a few mechanistic models developed for micro end milling processes [21–24], but these models do not consider the effects of edge radius, minimum chip thickness, elastic recovery, and tool dynamics together.

The objective of this paper is to develop a novel mechanistic micro-milling cutting force model, based on the shearing and ploughing-dominant cutting force regimes, that considers different effects, such as elastic recovery, run-out and dynamics. The mechanistic approach for cutting force modeling has been very effective for parameter estimation, force prediction, process monitoring and control, and understanding of the cutting process. Therefore, development of a new mechanistic micro end milling force model is important and will be useful for process understanding and monitoring/control.

Micro end mills have small tool tip diameters; therefore, impact hammer testing cannot be applied directly to the micro end mills, making it difficult to predict the tool tip dynamics. To overcome this, the receptance coupling (RC) technique is employed to mathematically couple the spindle/micro-machine and arbitrary micro end mills with different geometries in the prediction of dynamic forces and vibrations.

We first identify the critical chip thickness, based on the edge radius and the experimentally obtained forces vs. feed rate curve. For the shearing-dominant cutting regime, i.e. chip thickness greater than the critical thickness, we use the conventional sharp-edge theorem to identify the cutting constants by performing curve fittings from the experimental data. When the chip thickness is smaller than the critical chip thickness, we consider a model for the ploughing-dominant cutting regime. We introduce the ploughing coefficient based on the ploughed area. The elastic recovery rate of the workpiece is experimentally identified using a conical indenter and by observing the elastic deformation after the scratch tests. The cutting force model is verified for Aluminum 6061 (Al6061).

The organization of the paper is as follows: Section 2 depicts the experimental setup. Section 3 describes the methodology for predicting shearing and ploughing-dominant cutting forces through mechanistic modeling, including the effects of the tool tip dynamics, elastic recovery, and run-out and compares the simulation with the experimentally obtained forces. Section 4 illustrates the assumptions and limitations associated with the model, and Section 5 concludes with the contributions.

2. Experimental setup

We have utilized an ultra precision vertical CNC milling machine (Kern Micro 2255) with a spindle that can rotate from 60,000 to 160,000 rev/min (rpm). The base of the machine is polymer concrete, which damps out external vibrations. Unlike many micro CNC systems, the CNC machine used in this study utilizes hybrid ball bearings, which provide higher stiffness and linearity, and an elaborate lubrication system that allows for temperature stability during the high-speed rotations. The accuracy of the stage is 1 μm. The experimental setup for this study is depicted in Fig. 1.

The micro-tools used in this study were uncoated tungsten carbide (WC) micro end mills with 500 μm diameter flat micro end mills (PMT TS-2-0200-S) with the helix and clearance angles of approximately 30° and 10°, respectively. The tool overhang length was 15 mm from the collet; and, this value remained constant so that the dynamics were not changed during the experiments. The scanning electron microscopy (SEM) picture of the tip of the 500 μm diameter carbide end mill is shown in Fig. 2. The edge radius of the tools was measured from the SEM pictures and observed to be approximately 2 μm.

Several sensors, such as a table dynamometer, an acoustic emission sensor, accelerometers and capacitance sensors, and an optical vision system were used to capture various signals and monitor the cutting processes. The piezo-electric table dynamometer (Kistler 9256C2) with an accuracy of 0.002 N measured the micro-cutting forces. The charge signals generated from the force sensor were fed into the charge amplifiers (Kistler 9025B), which converted the charge signals into voltage signals. The calibration of the table dynamometer was performed using both modal impact hammer tests (Dytran 5800SL) and a force gauge (Omega DFG51-2) to verify the force measurement. The sensitivity of the dynamometer was 26 pC/N for X and Y directions. The noise level was approximately 0.005 N which was insignificant compared to the cutting forces. The frequency bandwidth of the dynamometer was found to be approximately 1500 Hz (Fig. 3) from the impact hammer tests.

The zero point in the Z direction was found by moving the rotating tool down very slowly and looking at the acoustic emission (AE) signal carefully. As soon as the tool touched the workpiece, a sudden jump in the AE signal was observed, and the position was set to zero. The forces were preprocessed by subtracting air cutting forces from the measured cutting forces through synchronization at each revolution of the spindle using