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Slip-line field model of micro-cutting process with round tool edge effect

Xiaoliang Jin, Yusuf Altintas*

Manufacturing Automation Laboratory, Department of Mechanical Engineering, University of British Columbia, 2329 West Mall, Vancouver, B.C. V6T 1Z4, Canada

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ABSTRACT

This paper presents a slip-line field model which considers the stress variation in the material deformation region due to the tool edge radius effect. The Johnson–Cook constitutive model is applied to obtain the shear flow stress and hydrostatic pressure as functions of strain, strain-rate, and temperature in the primary shear zone. The friction parameters between the rake face and chip are identified from cutting tests. The sticking and sliding contact zones between the tool and chip are considered in the secondary shear zone. The total cutting forces are evaluated by integrating the forces along the entire chip-rake face contact zone and the ploughing force caused by the round edge. The proposed model is experimentally verified by a series of cutting force measurements conducted during micro-turning tests. Micro-cutting process is analyzed from a series of slip-line field simulations.

1. Introduction

There has been an increasing demand for high-accuracy miniaturized components in the automotive, biomedical, electronics, and sensor industries. The miniature components usually have complex geometry with small dimensions requiring micron level accuracy. The manufacturing method commonly used for the production of micro-structured components is photolithography and ion beam etching. However, these methods are time consuming and limited to a few silicon-based materials with planar geometries. Compared to chemical manufacturing processes, the micro-cutting has the advantage of fabricating small components with complex three-dimensional features in a broad range of materials.

The chip loads and depth of cuts are typically within the range of 25 μm in micro-cutting applications. Since the cutting edge is typically ground with a 5–20 μm radius, the assumption of having an infinitely sharp cutting edge is not valid in modeling the mechanics of micro-cutting operations. The same argument is valid in finish machining of hardened steel and thermal resistant alloys where the chip loads are comparable to the radius of the cutting edge. The chip is partially sheared and ploughed with excessive plastic deformation around the cutting edge, which needs to be modeled for the accurate prediction of process force, stress, and strain.

The previous cutting mechanics models reveal that the chip formation is due to the shearing of the work material ahead of the tool. Merchant (1945) developed an orthogonal cutting model assuming that the shear zone was a thin plane. Lee and Shaffer (1951) proposed a triangular slip-line field model based on the rigid-perfect plastic material assumption. Childs (1980) incorporated the elastic contact between the tool and chip in the slip-line field model, leading to improved prediction of the process mechanics. Oxley (1989) presented a "Parallel-sided shear zone" model and considered the effects of strain, strain-rate, and temperature on the shear flow stress of the material. Adibi-Sedeh et al. (2003) extended Oxley's analysis by applying the Johnson–Cook material model, history-dependent power material model, and the Mechanical Threshold Stress model to match a broader class of materials. Childs (1998) compared different laws of flow stress variation with strain, strain-rate, and temperature for the stress and friction modeling in the primary and secondary shear zones. However, these models did not consider the effect of the tool edge radius.

Several publications investigated the effect of the tool edge preparation on the cutting process. Lee et al. (2008) proposed a mechanistic model of cutting process in micro-end-milling, which related the cutting force to the effective rake angle due to the round tool edge. Waldorf et al. (1998) proposed a slip-line field model considering a stable build-up region above the cutting edge. Manjunathaiah and Endres (2000) calculated the ploughing force by proposing the slip-line below the tool edge. Ren and Altintas (2000) presented the slip-line field model of cutting process with chamfered tools and considered the effects of strain, strain-rate, and temperature. Fang (2003a,b) proposed a generalized slip-line field model with a round edge tool to predict the shearing and ploughing forces. The effect of the round cutting edge on the cutting process has also been analyzed using Finite Element (FE) methods, which led to the prediction of chip formation, strain, temperature, and stress distributions. Özel and Zeren (2005) studied the FE modeling and simulation of orthogonal cutting of AISI 1045 steel by

* Corresponding author. Tel.: +1 604 822 5622; fax: +1 604 822 2403.
E-mail address: altintas@mech.ubc.ca (Y. Altintas).

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Nomenclature

η_1, η_2	angle of slip-lines DH, HJ (°)
θ_S	angle to determine the material separation point on the tool's round edge (°)
A	plastic equivalent strain in Johnson–Cook constitutive model (MPa)
B	strain-related constant in Johnson–Cook constitutive model (MPa)
C	strain-rate sensitivity constant in Johnson–Cook constitutive model
m	thermal softening parameter in Johnson–Cook constitutive model
n	strain-hardening parameter in Johnson–Cook constitutive model
σ	effective flow stress of workpiece material (MPa)
ε	effective strain of workpiece material
$\dot{\varepsilon}$	effective strain rate of workpiece material (s^{-1})
$\dot{\varepsilon}_0$	reference of effective strain rate of workpiece material (s^{-1})
T	temperature of workpiece material (°C)
T_r	initial work material temperature (°C)
T_m	melting temperature of workpiece material (°C)
k	shear flow stress of workpiece material (MPa)
γ	shear strain of workpiece material
$\dot{\gamma}$	shear strain-rate of workpiece material (s^{-1})
p	hydrostatic pressure of workpiece material (MPa)
$\partial\alpha$	infinitesimal distance along α slip-line (μm)
$\partial\beta$	infinitesimal distance along β slip-line (μm)
ψ	inclination angle of the slip-lines (°)
α	tool rake angle (°)
V	cutting velocity of the material (m/s)
V_{S1}	initial shear velocity of the material (m/s)
V_{S2}	final shear velocity of the material (m/s)
V_N	normal velocity of the material (m/s)
ϕ_B	shear angle at point B (°)
V_t	total change of shear velocity (m/s)
$\angle KCB$	intersection angle between slip-line KC and tool rake face (°)
τ	tool–chip frictional shear stresses in the sticking contact region (MPa)
μ	coulomb friction coefficient in the sliding contact region
r	radial distance along α slip-line in the primary shear zone (μm)
ϕ	inclination angle of α slip-line with respect to the vertical direction (°)
h	thickness of the primary shear zone (μm)
q	index of shear velocity change in the primary shear zone
c	specific heat of the workpiece material ($J\,kg^{-1}\,K^{-1}$)
ρ	density of the workpiece material (kg/m^3)
β_T	fraction of the deformation energy contributing to the temperature increase
R	radius of the slip-line at the boundary of the shear zone (μm)
R_{BJ}	radius of slip-line BJ (μm)
λ	intersection angle between GJ and the back surface of the chip (°)
κ	chip ratio
R, G, P^*, Q^*, L	matrix operators for slip-line determination
χ	column vector representing the slip-line
σ_n	normal stress on the rake face (MPa)
F_t	tangential force (N)
F_f	feed force (N)
t	uncut chip thickness (μm)
w	width of cut (mm)

using explicit Arbitrary Lagrangian Eulerian (ALE) method. Childs (2006) conducted the FE simulation of metal cutting and analyzed the effects of material properties, chip/tool friction conditions, tool rake angle and cutting edge radius on the chip formation. Woon et al. (2008) investigated the effect of tool edge radius on the frictional contact and flow stagnation phenomenon in micro-cutting through FE modeling approach.

This paper presents a slip-line field model for the micro-cutting process with a round edge cutting tool. The model includes the effect of strain, strain rate, and temperature on the shear flow stress of the material. The chip curling, sticking and sliding contact along the tool rake face, and the ploughing effect under the material separation point are considered.

2. Slip-line field model

The material deformation region in the cutting process is divided into three zones: the primary shear zone, secondary shear zone, and tertiary zone. The shape of the slip-line field with tool's round edge effect was originally proposed by Fang (2003a,b). The thickness of the primary shear zone was influenced by the tool edge radius in his model. However, the material was considered to be rigid plastic with constant shear flow stress, and the tool–chip frictional shear stress along each section of the rake face was assumed to be constant. Due to the high speed and large deformation of the material in the micro-cutting process, the effects of strain, strain-rate, and temperature on the cutting process are considered in the proposed model along the sticking and sliding contact region between the tool and workpiece.

The slip-line field model of orthogonal micro-cutting process with a round edge tool is shown in Fig. 1. Plane strain deformation and steady state cutting conditions are assumed. The primary shear zone consists of three regions: triangular region QEG is due to the pre-flow effect reported by Armarego and Brown (1969), since line QG is a stress-free boundary, all of the slip-lines in QEG intersect with QG at a 45° angle. Green (1954) proved that region GJNE

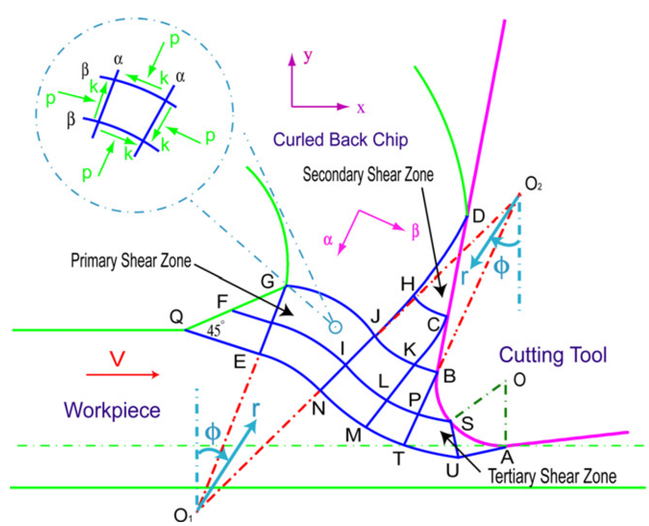

Fig. 1. Slip-line field model of orthogonal micro-cutting process with round tool edge: primary shear zone [GJBTNEQ], secondary shear zone [BCDHJK], tertiary shear zone [BSAUTP].