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Finite element analysis of the influence of tool edge radius on size effect in orthogonal micro-cutting process

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Abstract

The size effect in metal cutting is evident in the nonlinear scaling phenomenon observed in the specific cutting energy with decrease in uncut chip thickness. It has been argued by many researchers that this scaling phenomenon is caused mainly by the cutting tool edge radius, which purportedly affects the micro-cutting process by altering the effective rake angle, enhancing the plowing effect or introducing an indenting force component. However, the phenomenological reasons why the tool edge radius causes size effect and the relationship between the tool edge radius and the characteristic length scale associated with the size effect in micro-cutting has not been sufficiently clarified. In this paper, a strain gradient plasticity-based finite element model of orthogonal micro-cutting of Al5083-H116 alloy developed recently is used to examine fundamentally the influence of tool edge radius on size effect. The applicability of two length scales—tool edge radius and the material length scale l in strain gradient plasticity—are also examined via analysis of data available in the literature.

Keywords: Tool edge radius; Micro-cutting; Size effect; Strain gradient; Finite element

1. Introduction

The size effect in metal cutting is characterized by a nonlinear increase in the specific cutting energy, i.e. energy per unit volume with decrease in uncut chip thickness. This effect is especially prominent when cutting at micron level. Many researchers have attempted to explain this scaling phenomenon in terms of material strengthening mechanisms. Backer et al. [1] attributed the size effect to significantly reduced number of imperfections encountered when deformation takes place in a small volume. Hence, they argued that the material strength would be expected to increase and approach the theoretical strength when the uncut chip thickness is decreased. Kopalinsky and Oxley [2] and Marusich [3] attributed the size effect in machining to an increase in the shear strength of the workpiece material due to a decrease in the tool-chip interface temperature as the uncut chip thickness is decreased. Larsen-Basse and Oxley [4] attributed the size effect to material strengthening due to an increase in the strain rate in the primary shear zone with decrease in uncut chip thickness. Fang [5] presented a complex slip line model for orthogonal machining and attributed the size effect to the material constitutive behavior of varying shear flow stress with uncut chip thickness. Recently, Dinesh et al. [6] linked the size effect observed in micro-/nano-indentation to that in machining. The increase in hardness of a metallic material with decrease in indentation depth is a consequence of the dependence of flow stress of the metal on the strain gradient in the deformation zone. They suggested that the size-effect in machining can also be explained by the theory of strain-gradient plasticity since strain gradients in machining are very intense. Building upon the work in Ref. [6], Joshi and Melkote [7] presented an analytical model for orthogonal cutting that incorporates a material constitutive law with strain gradient effects. Liu and Melkote [8] attributed the size effect to strain gradient strengthening of the material when cutting at small uncut chip thickness levels. They presented a strain gradient based finite element model for micro-scale orthogonal cutting. Their simulation results predict a sizeable strain

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Nomenclature

b	Burgers vector (nm)
σ	flow stress (MPa)
σ_e	effective stress
σ'	deviatoric stress
σ_{ref}	reference yield stress (MPa)
δ_{ij}	Kronecker tensor
ρ	dislocation density
ρ_s	statistically stored dislocation density
ρ_g	density of geometrically necessary dislocations
G	shear modulus
α	empirical constant
η	effective strain gradient
η_{ijk}	strain gradient tensor
η'_{ijk}	deviatoric strain gradient tensor
ε	effective (true) strain
$\dot{\varepsilon}$	effective strain rate
$\dot{\varepsilon}_o$	reference strain rate
ε^p	effective plastic strain
l	characteristic material length
μ	friction coefficient
s	frictional shear stress
τ^*	limiting shear stress in Coulomb friction model
p	contact pressure
ξ_i	local coordinates in mesoscale cell
v	volume of the mesoscale cell
$\dot{Q}$	volume heat flux
T^*	dimensionless temperature in Johnson–Cook equation $((T - T_o)/(T_m - T_o))$
T_o	to ambient temperature
T_m	melting temperature
A	material constant in Johnson–Cook equation
B	material constant in Johnson–Cook equation
c	material constant in Johnson–Cook equation
n	material constant in Johnson–Cook equation
m	material constant in Johnson–Cook equation
ρ_m	material density
C_p	specific heat capacity
K	thermal conductivity
$\dot{U}$	material time rate of internal thermal energy

gradient strengthening effect in microcutting. This model was recently validated through micro-cutting experiments [8].

While these researchers believed that the increase in material shear strength with decrease in uncut chip thickness is responsible for the size effect, others have argued that the sharp tool assumption commonly made in analyzing cutting processes causes the nonlinear scaling effect. Since the edge radius of a cutting tool does become comparable to or is sometimes greater than the uncut chip thickness when the uncut chip thickness is reduced to the micron level, the sharp tool assumption is no longer valid. The effect of tool edge radius on the cutting process should therefore be taken into account when making shear strength calculations.

The existence of a ploughing mechanism, which is believed to be caused by the cutting edge radius, has been considered by many researchers [9–16] to be the primary cause of size effect. Thomsen et al. [9] proposed the concept of a separable ploughing force component not contributing to chip formation and estimated this force through the intercept obtained by extrapolating the cutting force to zero uncut chip thickness. Albrecht [10,11] went on to propose that two separate ploughing mechanisms occur simultaneously, one on the rake face and the other around the tool edge radius. Connolly and Rubenstein [13] modeled ploughing based on the assumption that material flowing under the edge radius was deformed by an extrusion-like process. Wu [14] modeled the ploughing force component to be proportional to the volume of material forced around the blunt edge and under the tool. Endres et al. [15] refined this model to obtain the proportional ploughing force component through a parameter estimation routine. Waldorf [16] developed a slip line model to describe the effects of tool edge radius and tool flank area on the cutting force.

Masuko [17] introduced the concept of an additional force component necessary to cause the cutting edge to penetrate the workpiece as an indenter. The indenting force component R_n, shown in Fig. 1, is considered to be independent of the uncut chip thickness. Therefore, he concluded that this indenting force was responsible for the size effect.

The above models assume that the ploughing/indenting effects are separable. However, great difficulty remains in that this force component cannot be measured directly by available methods such as the extrapolation technique [9] or the feed dwell approach [18].

Lucca et al. [19] experimentally examined the dissipation of mechanical energy in orthogonal ultra-precision flycutting of aluminum alloy 6061-T6 over depths of cut ranging from 0.01 to 20 μm at a cutting speed of 48 m/min. Their force data suggest that the process transitions from a cutting-dominant process to a ploughing/sliding indentation-dominant process. Tool edge radius was seen to have a

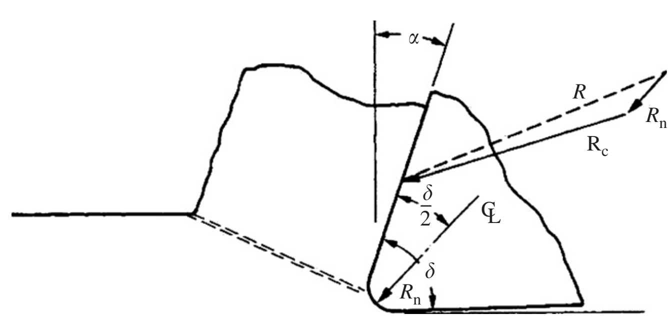

Fig. 1. Illustration of additional indenting force component [17].