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Investigations of critical cutting speed and ductile-to-brittle transition mechanism for workpiece material in ultra-high speed machining

Bing Wang [a,b], Zhanqiang Liu [a,b,*], Guosheng Su [c], Qinghua Song [a,b], Xing Ai [a,b]

[a] School of Mechanical Engineering, Shandong University, Jinan 250061, China
[b] Key Laboratory of High Efficiency and Clean Mechanical Manufacture (Shandong University), Ministry of Education, China
[c] School of Mechanical and Automotive Engineering, Qilu University of Technology, Jinan 250353, China

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ABSTRACT

This paper investigates the brittle removal mechanism of ductile materials in ultra-high speed machining (UHSM). Firstly, a predictive model of critical cutting speed for UHSM is proposed with the theory of stress wave propagation. The predicted critical cutting speed for ductile-to-brittle transition of ductile materials is then validated by machining experiments of 7050-T7451 aluminum alloy at the cutting speeds ranging from 50 m/min to 8000 m/min. The experimental results show that fragmented chips are produced above the critical cutting speed of 5000 m/min for 7050-T7451 aluminum alloy. The scanning electron microscopic (SEM) images of chips, chip roots and finished workpiece surfaces are observed and analyzed. Large amounts of brittle cracks and cleavage steps are observed on the fragmented chip surface obtained under the ultra-high cutting speed. Due to the remained brittle cracks, the finished surface quality obtained with UHSM is worse than that obtained with high speed machining. Secondly, the specific energy models for the chip formation are proposed and validated by experiments under ductile regime machining and brittle regime machining, respectively. The specific energies consumed for continuous and serrated chip formation mainly include plastic deformation energy located in the primary shear zone, the friction work between the tool–chip interface, and the chip kinetic energy. The plastic deformation energy accounts for the largest proportion among the total specific energy. Comparatively, the specific energy consumed during fragmented chip formation mainly includes the local kinetic energy of fragments and fracture surface energy. When the chip morphology evolves from serrated to fragmented one, the specific energy consumed reduces substantially, which demonstrates that the UHSM is beneficial for the energy saving. Lastly, taking both of the material removal efficiency and machined surface quality into consideration, the UHSM is recommended to be applied in rough machining or semi-finishing, while high speed machining is recommended to be applied in finishing process. This research firstly reveals the control mechanism for ductile-to-brittle transition of ductile materials under critical cutting speed (i.e. critical strain rate) considering solid mechanics and metal cutting principles as well as energy consumption simultaneously. This paper is enticing from both engineering and analytical perspectives aimed at revealing the mechanism of UHSM and instructing the optimization of machining parameters.

1. Introduction

The dynamic properties of materials under high strain rate have attracted wide attention in recent years. The solutions of many practical problems rely on the knowledge of material performance under dynamic loading. These practical problems include ballistic penetration, engineering blasting, earthquake, nuclear explosion, micro-meteorite impact on aircraft, ultra high speed machining (UHSM) and high speed forming, etc. [1–4]. The material dynamic response under UHSM is the research focus in this paper. Material responses under different dynamic loading conditions demonstrate distinctive mechanical properties compared with its static and quasi-static responses. Investigation of the material dynamic response makes great sense in not only predicting the material deformation and failure process, but also seeking the application of different material properties under high strain rate [5–7].

The ductility and brittleness are significant mechanical properties of materials and they determine the material deformation and

* Corresponding author at: School of Mechanical Engineering, Shandong University, Jinan 250061, China. Tel.: +86 531 88393206; fax: +86 531 88392045.
E-mail address: melius@sdu.edu.cn (Z. Liu).

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Nomenclature

A	initial yield stress (MPa)
A_0	original transverse area (mm^2)
A_s	sectional area of the primary shear zone (mm^2)
A_t	true transverse area of bar after impact (mm^2)
A'	ratio of the fragment surface area to its volume
a_c	uncut chip thickness (mm)
a_{ch}	chip thickness (mm)
a_w	cutting width parallel with the cutting edge (mm)
B	hardening modulus (MPa)
C	strain rate dependency coefficient
c	specific heat ($J\,kg^{-1}\,K^{-1}$)
c_p	plastic wave propagation velocity (m/min)
d_1	diameter of slot milling cutter (mm)
d_2	width of workpiece (mm)
dM	mass of a cylinder shell in the compressed chip region (kg)
E	elasticity modulus (GPa)
$E(A')$	total energy density for the formation of fragmented chips (GN/m^2)
f	friction force between tool–chip interface (N)
F_s	shear force along the primary shear zone (N)
G_s	chip serrated degree
h	discontinuous section height of serrated chip (mm)
H	maximum height of serrated chip (mm)
k	material thermal conductivity ($W\,m^{-1}\,K^{-1}$)
K_{Ic}	dynamic plane strain fracture toughness ($MPa\,m^{-1/2}$)
K_{Ic}'	static plane strain fracture toughness ($MPa\,m^{-1/2}$)
L	upper boundary displacement of adiabatic shear band (mm)
l	shear zone width (mm)
m	thermal softening coefficient
n	strain hardening coefficient
r	cylinder shell radius of compressed chip region (mm)
$\dot{r}$	compression rate of the cylinder shell radius r (m/s)
S	width of adiabatic shear band (mm)
T, T_1, T_2, T_3, T_4	current temperature (K)
T_m	melting temperature of workpiece material (K)
T_r	room temperature (K)
ΔT	incremental temperature (K)
V	cutting speed (m/min)
V_c	chip sliding speed along tool rake face (m/min)
V_s	chip shear speed along the primary shear zone (m/min)
V_{imp}	critical impact speed (m/min)
V_{imp_c}	critical cutting speed of UHSM (m/min)
V^*	shear speed on the shear band boundary (m/min)
u	displacement of the location at a distance x from the bar end (mm)
W_f	specific friction work (GN/m^2)
W_k	specific kinetic energy of the flowing chip (GN/m^2)
W_p	specific energy of plastic deformation (GN/m^2)
Γ	energy density of new fragment surface (GN/m^2)
Φ	shear angle (deg)
Ψ	local kinetic energy density for the fragmented chip formation (GN/m^2)
Ψ'	kinetic energy about the center of the compressed cylinder chip (J)
α, θ	material constants
β	friction angle (deg)
γ	shear strain
γ_0	tool rake angle (deg)
ε	plastic strain
ε_u	strain corresponding to tensile strength
$\bar{\varepsilon}$	equivalent plastic strain
$\dot{\varepsilon}$, $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$, $\dot{\varepsilon}_4$	strain rate (s^{-1})
$\dot{\bar{\varepsilon}}$	equivalent strain rate (s^{-1})
$\dot{\bar{\varepsilon}}_0$	reference strain rate (s^{-1})
η	Taylor and Quinney coefficient
λ	coefficient of thermal diffusivity (m^2/s)
μ	heat distribution coefficient
ρ	material density (kg/m^3)
σ	flow stress (MPa)
σ_0	engineering nominal stress (MPa)
σ_s	yield strength (MPa)
σ_b	tensile strength (MPa)
$\bar{\sigma}$	equivalent flow stress (MPa)
τ	shear stress (MPa)
τ_0	reference shear stress (MPa)
$(\tau_s)_{max}$	maximum shear stress in primary shear zone (MPa)
$\bar{\tau}_s$	average shear stress in the primary zone (MPa)
υ	longitudinal wave velocity (m/min)
χ	specific surface energy ($N\,m^{-1}$)

failure mode. However, the ductility and brittleness of materials are relative concepts because these material properties change with different deformation conditions. For a given material, the main deformation conditions include ambient temperature, deformation strain rate and specimen size, etc. Atkins and Mai [8] reviewed the effects of body size and material properties on the deformation state. Their review shows that materials respond in such six ways as simple elastic deformation, elastic fracture, elastoplastic flow, elastoplastic fracture, plastic flow and plastic fracture, etc. For the fixed body size made of given material, the deformation modes are controlled by the material mechanical properties which are altered by deformation rate, temperature, superimposed hydrostatic stress, etc. Increase of deformation rate and decrease of deformation temperature usually promote brittle behavior for a given material. Edwards [9] researched the properties of metals under different strain rates, which showed that the operative deformation mechanism evolves from isothermal in static and quasi-static deformation rates, to adiabatic shear banding and twinning in moderate strain rates. While the deformation behavior of metals shifts to fracture phenomenon including fragmentation and spalling under ultra-high strain rates. Dümmer et al. [10] studied the mechanical behavior of polycrystalline tungsten loaded at quasi-static ($3\times10^{-3}\,s^{-1}$) and high dynamic (10^3–$4\times10^3\,s^{-1}$) strain rates. Three deformation mechanisms were identified as slip, twinning, and inter-granular fracture with the strain rate increasing. They found that low strain rate deformation yields limited damage at strains as high as 0.25, whereas high strain rate deformation leads to material catastrophic failure at strains between 0.05 and 0.10. Tanguy et al. [11,12] investigated the ductile-to-brittle transition of A508 steel based on experimental and numerical simulation of Charpy impact test. Mechanical properties and fracture modes of A508 steel were investigated over a wide range of temperatures and strain rates. They found that A508 steel undergoes a reduction in fracture toughness with the decrease of temperature due to the change in failure mode from microvoids coalescence to cleavage fracture. Roth and Mohr [13] performed static and dynamic experiments on specimens of advanced high strength steel sheets to investigate the effect of loading rate on fracture initiation. Their experimental results of DP590 and TRIP780 high strength steels for notched tension and tension with a central hole indicate that the