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Ductile Mode Cutting of Brittle Materials

Springer

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Preface

Brittle material, in general, shows little ability to deform plastically and commonly fracture at or very near to the elastic limit. Usually, it is considerably stronger in compression than in tension. Nowadays, brittle material has been applied in numerous important industries including aerospace, oil and gas, precision engineering, optics, instruments, automotive, semiconductor, marine and micro-electromechanical systems. Meanwhile, there are rapid growing demands of its engineering applications due to unique and non-replicable material properties. It has attracted great interests from both engineers and academics for the sake of its excellent mechanical, electrical, optical, physical and chemical properties. However, it is very difficult to machine brittle material using conventional cutting technologies to obtain very smooth and damage-free surfaces due to its high hardness, high wear resistance and high toughness. In general, abrasive processes such as grinding, lapping and polishing are commonly used for fabricating the brittle material components. The demerits associated with those processes are poor machinability, subsurface damage, high manufacturing cost and time-consuming. Such that engineering applications of brittle material are largely limited. Naturally, questions on how to overcome this problem are surfacing up. Thereafter, a technology for efficiently cutting of brittle material is urgently needed for the industry.

Ductile mode cutting of brittle material is a very promising and well-recognized technology enabling to achieve high-quality and crack-free surface for the industry. But what is ductile mode cutting and how to achieve ductile mode cutting of brittle material? To answer those questions, this book is dedicated to an in-depth study and understanding of material removal behaviour in cutting of brittle material, where stock material is removed by plastic deformation rather than fracturing. Ductile mode cutting of brittle material can be achieved under certain cutting conditions, while crack-free and no subsurface-damage surfaces can be obtained simultaneously. The book intends to provide a comprehensive understanding to the research community, including ductile mode cutting fundamentals such as mechanism, characteristics, modelling and molecular dynamics simulation, ductile mode cutting applications such as silicon, glass, tungsten carbide and calcium fluoride, as well as hybrid ductile mode cutting like ultrasonic vibration and thermally assisted ductile mode cutting of brittle material. The book details ductile mode cutting of brittle material systematically in terms of fundamentals, engineering applications and hybrid ductile mode cutting techniques, which is structured and organized as:

Chapter 1: Literature review and state of the art in terms of ductile nature and plasticity of brittle material, ductile-to-brittle transition phenomena and mechanism, dislocation dynamics, crack propagation behaviour, ductile regime grinding and ductile mode cutting.
Chapter 2: Theoretical analysing of the mechanism of ductile mode cutting of brittle material, such as the coexisting crack propagation and dislocation extension in chip formation zone, large compressive stress and shear stress in cutting zone, fracture mechanics, yield strength enhancement by dislocation hardening and strain gradient, and ductile mode cutting conditions as well.
Chapter 3: Experimental investigation on ductile mode cutting characteristics including grooving surface morphology, material removal mechanism and material removal mode, and tool wear mechanism.
Chapter 4: Mathematical modelling of ductile mode cutting of brittle material to predict critical undeformed chip thickness based on work material's properties, or cutting tool geometry and cutting conditions used, as well experimental verification in terms of grooved surface topography, chip morphology, critical depth of cut and material removal ratio.
Chapter 5: Fundamentals and review of molecular dynamics including interatomic potentials adopted for brittle material modelling, with examples of molecular dynamics simulations performed on silicon and silicon carbide, as well as theoretical techniques to determine stress distributions during cutting of brittle material.
Chapter 6: Experimental studies on cutting characteristics of single crystal silicon wafers including tool edge radius effect on critical undeformed chip thickness for ductile mode cutting, upper bound for diamond tool edge radius achieving ductile mode cutting of silicon, and ductile mode cutting performance.
Chapter 7: Experimental studies of glass cutting characteristics through grooving, groove turning and ultrasonic vibration-assisted cutting of soda-lime glass in terms of nanometric cutting mode, machined surface topography, surface roughness, chip formation and tool wear.
Chapter 8: Material characteristics analysing of tungsten carbide and experimental studies on cutting performance of tungsten carbide under normal and high cutting speed at nanometric scale chip formation in terms of cutting force, machined surface topography, surface roughness, chip formation and tool wear.
Chapter 9: Understanding of optical surface generation on calcium fluoride single crystals, including cutting condition assessment and material constraints, surface evaluation techniques and anisotropic machined surface morphology, theoretical simulations, and advanced machining techniques.
Chapter 10: Analytical modelling of critical undeformed chip thickness prediction in ultrasonic vibration-assisted cutting based on the variation of specific cutting energy in both ductile mode cutting and brittle mode cutting of brittle material, as well as experimental verification.

Chapter 11: Experimental investigations on 1D ultrasonic vibration-assisted grooving of tungsten carbide in terms of grooved surface topography and critical depth of cut, 1D ultrasonic vibration-assisted cutting of tungsten carbide in terms of cutting force, chip formation and surface roughness, and 2D ultrasonic vibration-assisted cutting performance in terms of effects of different vibration amplitude combinations and effects of diamond tool types on cutting performance of tungsten carbide.
Chapter 12: Analysing technological advancement in thermally assisted machining techniques towards micromachining and effects of thermal assistance on the cutting process in terms of enhancing the plasticity of work material and reducing tool wear in cutting of brittle material.
Chapter 13: Summarizing ductile mode cutting of brittle material in terms of fundamentals, engineering applications and hybrid ductile mode cutting techniques, as well as discussion of future development in the cutting of brittle material.

The book can serve as an informative and systematic reference for academics, engineers, researchers and professionals related to the cutting of brittle material and applications. More extensive theoretical, experimental and simulation studies on ductile mode cutting should be extended to more advanced and newly emerged brittle material. Novel and breakthrough technologies on hybrid manufacturing/machining processes need to be innovated and developed to largely improve ductile mode cutting performance and machinability of brittle material. It will help to eliminate manufacturing barriers effectively and bloom the industrial demands significantly.

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The original version of the book was revised: inadvertently published with wrong author spelling. The correction to the book is available at https://doi.org/10.1007/978-981-32-9836-1_14

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Correction to: Ductile Mode Cutting of Brittle Materials C1

Nomenclature

A	Cutting edge temperature rise factor
	Amplitude
	Material-dependent constant in the Born–Mayer interatomic potential
	Ionic interatomic strength parameter
	Indentation area
A_1, A_2	Cross-sectional areas of the ridge
A_c	Undeformed chip area
A_f	Tool–workpiece contact area
A_s	Total surface area of cracks
A_V	Cross-sectional area of the groove
A_W	The value of A_V subtracted by $A_1 + A_2$
B	Factor of the material microstructural parameters
B_{ijk}	Interaction strength
C	Contiguity of the WC grains
	Dislocation constant
	Ionic crystal energy-conversion constant
C_{11}	Elastic constant
C_l	Lateral crack length
C_m	Median crack length
D	Cohesion energy
D_{ij}	Charge–dipole attraction strength
D_0	Dimer energy
E	Elastic modulus
E_{tot}	Total energy of a system
F	Applied tensile force
	Machining force
F_c	Cutting force in cutting direction
F_{crit}	Critical force at crack-shielding zone boundary
F_f	Friction force on tool face
$\boldsymbol{F}_i$	Force acting on atom

F_n	Normal force on tool–chip interface
F_N	Normal forces on the atoms at the tool–chip interface
F_{ns}	Normal force on shear plane
$\mathbf{F}^{\mathrm{P}}$	Plastic shear
F_r	Resultant tool force
F_s	Shear force on the shear plane
F_S	Shear forces on the atoms along the shear plane
F_t	Thrust force or force normal to cutting direction and machined surface
F_x, F_y, F_z	Cutting force in X, Y and Z directions
G_i	Atom embedding energy
H	Hardness of the alloy
H_{ij}	Steric repulsion strength
H_m	Hardness of the binder phase in WC-Co
H_o	Function of the properties of the individual phases of the alloy
H_{owc}	Hardness of binderless polycrystalline WC
J	Thermal number
K_C	Fracture toughness
K_I	Stress intensity factor for the opening mode (mode I)
K_{om}	Hall–Petch parameter of the binder phase Co
K_{wc}	Hall–Petch parameter of WC
K_y	Function of the alloy composition and microstructural parameters
L	Mean dislocation spacing
	Thickness of crack-shielding zone
	Length of material to be removed
L_e	Elastic deformation length
L_x	Instantaneous displacement of tool–workpiece interface
N	Plastic work hardening exponent
	Number of atoms in the system
	Spindle speed in revolutions per minute
P	Cooling capacity
	Indentation load
P_c	Load at critical point aligned in the direction of median crack
P_f	Rate of heat generation in the second deformation zone
P_m	Rate of energy consumption during machining
P_s	Rate of heat generation in the primary deformation zone
R	Material's fracture energy
	Tool corner nose radius
R_a	Surface roughness
T	Temperature
U	Potential energy function
$U_{ij}^{(2)}$	Two-body term in Vashishta interatomic potential
$U_{ij}^{(3)}$	Three-body term in Vashishta interatomic potential
U_r	Repulsion energy between atoms i and j
U_a	Attraction energy between atoms i and j
V_c	Simulation cutting speed

V_{crit}	Critical nominal speed in vibration-assisted machining
V_{ij}	Interatomic bond energies between atoms *i* and *j*
V_{wc}	Volume fraction of the WC phase
W	Width of the finite body
	Width of cut
W_c	Critical width of cut
W_{ij}	van der Waals interaction strength
X	Cartesian co-ordinate
Y	Geometric factor
	Cartesian co-ordinate
Z	Cartesian co-ordinate
Z_e	Distance from tool centre to fracture-pit transition on uncut shoulder
Z_{eff}	Distance from tool centre to fracture-pit transition on uncut shoulder
Z_{ij}	Effective electronic charges
a	Lattice constant
	Elastic modulus for the Morse interatomic potential
	Cutting directional vibration amplitude
a_c	Undeformed chip thickness
	Uncut chip thickness
a_o	Chip thickness
	Depth of cut
	Lattice constant
a_w	Width of cut
b	Distance between crack tip and the element
	Lattice constant
	Thrust directional vibration amplitude
	Burgers vector
b_{Co}	Burgers vector of dislocation for cobalt
b_{ij}	Bond order
c	Material specific heat capacity
	Lattice constant
	Length of half-crack
c_1, c_2, c_3	Constant
d	Mean WC grain size
d_c	Critical undeformed chip thickness
dk	Infinitesimally small random cutting edge
d_{max}	Maximum undeformed chip thickness
d_s	Spring-back thickness of machined surface by elastic recovery
d_e	Thickness of subsurface damage
dt_1	Undeformed chip thickness corresponding to the infinitesimally small cutting edge dk
$dxdy$	Element of a plate
$\bar{d}$	Average displacement

f	Dislocation fraction
	Function of strain
	Feed
	Feed rate
	Frequency
f_{ab}	Work material removal ratio
f_A	Attractive pair potential
f_c	Cut-off function
f_R	Repulsive pair potential
$f\left(\frac{a}{W}\right)$	Function of crack size
h	Thickness of material to be removed
$h_{\alpha\beta}$	Strain hardening factor
h_0	Self-hardening factor
k	Material thermal conductivity
	Interatomic spring constant
k_1, k_2	Scaling constant
k_{AB}	Shear flow stress along shear plane *AB*
k_B	Boltzmann constant
l	Characteristic material length
l_s	Shear plane length
m	Parameter of crystal material performance
	Atom mass
	Rate sensitivity factor
n	Crack's number within a finite plate
	Spindle rotation speed
	Refractive index
$\mathbf{n}$	Direction normal to the slip plane
n_c	Coefficient of heat conducting into tool
p	Pressure during machining
$\mathbf{p}_i$	Momentum of atom i
q	Power density of the heat source
q_i	Atomic charge of atom i
r	Tool cutting edge radius
r_B	Average radius of the Gaussian beam
r_c	Ratio of the undeformed chip thickness a_c to chip thickness a_o
r_e	Effective distance between atoms i and j
$\mathbf{r}_i$	Position of atom i
r_0	Material-dependent constant in the Born–Mayer interatomic potential
	Bond length in the Tersoff interatomic potential
	Workpiece outer radius
s	Slip direction
	Elastic recovery
t	Time
t_o	Undeformed chip thickness

u	Brittle–ductile transition factor
u_i	Displacement
v	Cutting velocity
	Cutting speed
v_c	Chip flow velocity
	Nominal cutting speed
v_f	Feed rate
v_i	Velocity of atom i
v_s	Shear velocity
v_t	True cutting speed
	Actual cutting speed in ultrasonic vibration-assisted cutting
v_u	Velocity of ultrasonic vibration
$\bar{v}$	Average dislocation velocity
w	Width of cut measured along the cutting edge
x_i	Cartesian reference frame
y_c	Average surface damage depth
	Critical depth of microfracture
Γ	Proportion of heat conducted from the chip formation zone into the workpiece
α	Inclined angle
	Clearance angle
	Nominal rake angle
α_e	Instantaneous effective rake angle
α_t	Empirical material coefficient
α_k	Angle between cutting velocity direction and the tangent at point K
β	Mean friction angle on tool face
	Slip system β
γ	Tool rake angle
	Plastic strain
	Angle between the crystal face and the slip direction
γ_e	Tool equivalent rake angle
γ_f	Radial rake angle
γ_k	Local tool rake angle corresponding to the infinitesimally small cutting edge dk
γ_{ne}	Actual working rake angle
γ_o	True rake angle
γ_p	Axial rake angle
γ_s	Specific surface energy
$\gamma^{(\alpha)}$	Slip-in-slip system α
$\bar{\partial}_i$	Forward gradient operator
ε	Effective strain
	Material-dependent energy constant parameter
ε_c	Critical value of composite strain at fracture
ε_{ij}	Strain tensor

ε_p	Plastic strain measured in the tensile direction
ε_r	Tool included angle or point angle
ε_p	Plastic strain rate
ε'_{ij}	Deviatoric strain tensor
ε_0	Permittivity of vacuum
ζ	Angle between the applied stress and the slip direction on the slip plane
η	Effective strain gradient
η_{ijk}	Strain gradient tensor
η_{ij}	Steric repulsion exponent term
η^H_{ijk}	Hydrostatic part of strain gradient tensor
η'_{ijk}	Deviatoric strain gradient tensor
θ	Angle between *X*-axis and line from crack tip to the element Angle between the applied stress and the normal to the slip plane Included sector angle
θ_e	Temperature in the chip formation zone
θ_f	Temperature rise at the tool–chip interface Tool clearance angle
θ_{jik}	Angle between $\mathbf{r}_{ij}$ and $\mathbf{r}_{ik}$
θ_m	Temperature rise at the tool cutting edge
θ_o	Initial workpiece temperature
θ_s	Temperature rise of material passing through the chip formation zone
κ'_r	Minor cutting edge angle
λ	True cutting edge inclination Screening length for Coulomb term in Vashishta potential Angle between the applied load and the slip plane Wavelength
λ_s	Cutting edge inclination
μ	Shear modulus
μ_f	Friction coefficient
v	Poisson's ratio
ξ	Screening length for charge–dipole term in Vashishta potential
ρ	Material density
ρ_{G}	Geometrically necessary dislocations density
ρ_{ij}	Ionic pair-dependent length parameter
ρ_S	Statistically stored dislocations density
ρ_T	Total dislocation density
ρ_t	Radius of curvature at crack tip of length *c*
ρ'	Total number of dislocations moved
ρ'_o	Mobile dislocations density
ρ_{ii}	Electron density at atom *i*
σ	Tensile stress Material-dependent distance constant parameter
σ_{cleave}	Cleavage stress at crack nucleation site

σ_{comp}	Compressive stress at crack nucleation site
σ_f	Critical tensile stress prior to brittle failure
	Stress of workpiece at tool flank face
σ_o	Constant characteristic of crystal material
σ_{ref}	Reference stress in uniaxial tension
σ_s	Mean normal stress in shear plane
σ_x	Normal stress in X-direction
σ_y	Normal stress in Y-direction
σ_z	Normal stress in Z-direction
σ_Y	Yield stress
τ	Shear stress
τ_e	Resolved shear stress
τ_c	Critical shear stress
τ_p	Peierls stress for dislocation motion
τ_{pair}	Peach–Koehler shear stress
τ_s	Shear stress on the curved shear plane
τ_{slip}	Resolved shear stress
τ_{xy}	Shear stress within the element
φ	Shear angle corresponding to the constant rake angle γ
	Angle between the applied stress and the normal to the cleavage plane
	Phase shift
φ_e	Equivalent shear angle corresponding to the equivalent rake angle γ_e
	Instantaneous shear angle
φ_k	Local shear angle corresponding to the infinitesimally small cutting edge dk
ψ	Peripheral cutting edge angle
	Angle between crystal face and axis of rotation for the slip system
ω	Crack angle
	Angular frequency
χ	Geometric constant
$2a$	Length of a crack in the centre of a finite body

Acronyms

ABOP	Analytical bond-order potential
AFM	Atomic force microscope
BDT	Brittle-to-ductile transition
BMC	Brittle mode cutting
B-NPD	Boron-doped nanobinderless polycrystalline diamond
BUE	Built-up edge
CBN	Cubic boron nitride
CC	Conventional cutting
CMP	Chemical–mechanical polishing
CN	Coordination number
CNC	Computer numerical control
CPFEM	Crystal plasticity finite element method
DBT	Ductile-to-brittle transition
DC	Ductile cutting
DFT	Density functional theory
DMC	Ductile mode cutting
DOC	Depth of cut
DRC	Ductile regime cutting
EAM	Embedded-atom method
EDS	Energy-dispersive X-ray spectrometer
ELACM	Excimer laser-assisted chemical machining
FEA	Finite element analysis
FEM	Finite element method
FFT	Fast Fourier transfer
HCP	Hexagonal-close-packed
HF	Hartree–Fock
HPPT	High-pressure phase transition
HV	Vickers hardness
IC	Integrity circuit
ISO	International Organization for Standardization
MD	Molecular dynamics

MEMS	Micro-electromechanical systems
NPD	Nanopolycrystalline diamond
NS	Normal sintered
OD	Outer diameter
OMIS	Optical measurement inspection system
PCD	Polycrystalline diamond
PZT	Piezoelectric transition
RMS	Root mean square
SCD	Single crystal diamond
SEM	Scanning electron microscope
SLS	Selective laser sintering
SPDT	Single-point diamond turning
SSD	Subsurface damage
TEM	Transmission electron microscopy
UCT	Undeformed chip thickness
UVC	Ultrasonic vibration-assisted cutting
WC	Tungsten carbide
	Tungsten monocarbide
WLI	White light interferometry
1D	One dimension
2D	Two dimension
μ-LAM	Micro-laser-assisted machining