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METAL CUTTING PRINCIPLES

SECOND EDITION

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Second Edition

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PREFACE TO THE SECOND EDITION

There were many important developments during the second half of the twentieth century, and these have been incorporated in the appropriate chapters of the first edition. In addition, five new chapters have been added. The first of these (Chapter 20) reviews several new developments in modeling the cutting process. The next two chapters have been added to cover two chip types not fully discussed in the first edition (wavy chips in Chapter 21 and sawtooth chips in Chapter 22). Chapter 23 provides a general discussion of the area of precision engineering, which has played an increasing role in production engineering since the first edition. The final chapter, Chapter 24, discusses a number of noncutting operations where the very unusual conditions associated with metal cutting may be used to advantage in other operations, some of these being as remote from the production of mechanical parts as the production of organic chemicals.

Tempe, Arizona M. C. S.

PREFACE TO THE FIRST EDITION

Metal cutting is one of the most important methods of removing unwanted material in the production of mechanical components. This treatment identifies the major problem areas and relates observed performance to fundamentals of physics, chemistry, materials behavior, and the engineering sciences of heat transfer, solid mechanics, and surface science (tribology).

The basic two-dimensional (orthogonal) cutting process is first analyzed in detail followed by consideration of representative three dimensional cutting operations. Special attention is directed toward cutting temperatures, tool wear and tool life, and the integrity of finished surfaces. Machining economics and optimization of cutting processes are discussed in terms of representative examples.

Cutting processes are unusually complex largely due to the fact that two basic operations occur simultaneously in close proximity with strong interaction:

1. large strain plastic deformation in a zone of concentrated shear
2. material transport along a heavily loaded region of relative motion between chip and tool

In general, several simplified models which emphasize different aspects of the problem such as thermal, material, and surface considerations are operative simultaneously with varying degrees of importance depending on specific machining conditions. Due to complexities of the problem, a general predictive theory is not possible. Instead of seeking the impossible, a more practical approach is adopted in which a wide variety of experiences are explained in fundamental terms. Thus, the aim is to illustrate how fundamental concepts may be used to explain observed results from carefully planned experiments and how solutions to new machining situations may be achieved by application of scientific principles. Where possible, theoretical discussions are kept simple by use of techniques such as dimensional analysis.

The book should serve as a valuable reference to those engaged in research in metal cutting or as a text in a graduate subject concerned with manufacturing engineering. The background material concerning the plastic flow and fracture of solid materials and the special behavior of surfaces contains many new ideas and should be of interest to a wider group of engineers than those engaged in production engineering.

This monograph began as a set of photo-offset lecture notes first published in 1950 by Technology Press (MIT, Cambridge, Mass.) with the title *Metal Cutting Principles*. Although these notes were issued in three successive editions (the third and last in 1954), they never appeared in complete form. For example, there was no Chapter 8. This was not because of any superstition attached to that number but because Chapter 8 was reserved for what has come to be known as the "shear angle problem" (also Chapter 8 in the present work). In the early 1950s there was considerable interest in this problem and always the hope that a satisfactory general solution was soon to be found. While there have been countless attempts, the ideal solution has never been found largely for reasons discussed in the present Chapter 8.

I have worked continuously on metal removal problems with many very talented graduate students for over thirty-five years (Massachusetts Institute of Technology (MIT), 1946–61; Carnegie Mellon University (CMU), 1961–78; and Arizona State University (ASU), 1978–). This book largely records and integrates their collective ideas and carefully performed experiments. Generous support for this research has been received from a number of industrial companies, the U.S. Government, and the three institutions with which I have been associated.

Metal cutting is a time honored activity having a rich literature much of which goes back well before the work of F. W. Taylor at the turn of the [twentieth] century. No attempt has been made to review all that has been written on a given subject. I have been selective in citing literature that seems to support points of view I consider closest to fact in each problem considered. Ideas and experimental results have been considered from a number of sources, and in each case I have tried to clearly acknowledge them throughout the book.

While I have done my best to eliminate errors of all types, I do not expect complete success in this endeavor and should appreciate being informed of errors which still persist.

I wish to acknowledge with thanks the efforts of Mr. Young Moon Lee of Kyungpook National University, Taegu, Korea, who critically reviewed the entire manuscript and uncovered many errors and inconsistencies. Special thanks are also due to Ms. Elinor M. Lindenberger of ASU for carefully typing most of the manuscript. My wife, Mary Jane, spent many hours editing the text, reading proofs, and generally improving the manuscript, for which I am most grateful.

M. C. S.

Tempe, Arizona
August 1983

SYMBOLS

A	area
	apparent area of contact
	constant in Eq. (9.11)
A_m	factor defined in Eq. (12.11)
A_R	real area of contact
A_S	area of shear plane
$\bar{A}$	area factor (a function of aspect ratio of slider, m/l in Fig. 12.17)
AB	chordal size of "ear" type chip (Fig. 18.8)
AB^*	nondimensional chip shape = AB/R_c (Fig. 18.8)
B	volume worn away (Chapter 11)
	Bainite
	constant in Eq. (9.11)
C	constant in Taylor tool life equation [Eq. (11.12)]
	stress concentration factor
	constraint factor for an indentor
	volume specific heat
	corner angle of milling cutter
	controlled-contact tool-face length
	concentration of additive in cutting fluid (volume fraction)
	cutting efficiency
C_e	end-cutting edge angle
C_s	side-cutting edge angle
$\bar{C}$	iron carbide (Fe_3C)
CE	chip equivalent (Chapter 17)
D	diameter
E	Young's modulus of elasticity
	output voltage from strain gage
F	force (fundamental dimension in dimensional analysis)
	shear force
	fraction failed in Weibull statistics

F_C	cutting force component parallel to tool face
F_o	probability of failure at given stress level
F_P	cutting force component in power direction (i.e., parallel to V)
F_Q	cutting force component in undeformed chip thickness direction
F_R	cutting force component perpendicular to F_P and F_Q
F_S	cutting force component parallel to shear plane
G	shear modulus of elasticity
H_B	Brinell hardness
H_K	Knoop hardness
H_M	Meyer hardness
H_{RA}	Rockwell A hardness
H_{RB}	Rockwell B hardness
H_{RC}	Rockwell C hardness
H_S	Moh's hardness
H_V	Vickers hardness
I	area moment of inertia
J	polar moment of inertia
	mechanical equivalent of heat
K	bulk modulus
	stress intensity factor in fracture mechanics
	spring constant $[FL^{-1}]$
	probability that a real contact will result in a wear particle
	ratio of (shear stress on shear plane)/(shear stress on tool face)
	incremental speed factor in machine tool drive
	pressure coefficient of ductility in Bridgman fracture equation
L	liquid phase
L	fundamental dimension for length in dimensional analysis
	nondimensional contact length (a'/t)
	helical length of cut in turning
	sliding length (Chapter 11)
	pitch length of helix (drill)
	active length of cutting edge (Fig. 17.32b)
	nondimensional velocity quantity in Chapter 12 = $Vl/2K$
M	drilling torque
	cost machinability ratio = $¢_1/¢_2$
M_f	temperature at which martensitic transformation is complete
	fracture torque in drilling
M_s	temperature at which martensitic transformation begins
M_T	twisting moment
$M^{\#}$	cost machinability ratio under cost optimum conditions
N	r.p.m.
	cycles to fracture
N_C	cutting force component perpendicular to tool face
N_F	nondimensional fracture number = $(\sigma^2 K)/(Eu^2 b)$ (Chapter 11)
N_o	characteristic life in Weibull statistics
N_S	cutting force component perpendicular to shear plane
N_W	wear number = BH/LP (Chapter 11)
P	pearlite

P	force
	principal stress in Griffith crack initiation analysis
	probability
P_f	brittle fracture load
P'_f	brittle fracture load per unit length
Q	energy input per unit time
	principal stress in Griffith crack initiation analysis
	total heat flux
R	resultant force on tool face
	profile radius at neck of tensile specimen
	heat partition coefficient in Chapter 12 = fraction of heat flowing to extensive member of sliding pair (R_1 for shear plane, R_2 for tool face)
	cost ratio = $xT_d + y/x$ in Chapter 19
	risk of rupture in Weibull statistics
	resistance (ohms)
	chip packing ratio = volume of chips/equivalent volume of uncut metal
R'	resultant force on shear plane
R_a	arithmetic average surface roughness
R_n	indenting force due to tool tip radius (Chapter 10)
	radius of principal cutting edge (Fig. 10.14)
R_t	maximum peak-to-valley surface roughness
R_{nP}	power component of R_n (Fig. 10.15)
R_{nQ}	feed component of R_n (Fig. 10.15)
S	Spherodite
S	normal tensile stress (based on original area A_o)
	percent surviving in Weibull statistics
	total saving with stepless machine tool drive
S_d	Steadite
T	tempered martensite
T	fundamental dimension (time) in dimensional analysis
	life in Taylor tool life Eq. (11.12)
	surface energy $[FL^{-1}]$
	absolute temperature
	drilling thrust
T_c	cutting time
T_d	down-time to change and reset tool
T_e	component of drill thrust due to "extrusion" at web
T_f	fracture thrust for drill
T_H	homologous temperature = absolute temperature/absolute melting temperature (both K)
T_m	velocity modified temperature
T_P	surface energy associated with plastic crack growth
$T^{\#}$	cost optimum tool life (min)
$T^{\#\#}$	production rate optimum tool life (min)
U	total cutting energy per unit time
	elastic energy stored at crack tip per unit length in Griffith analysis (Chapter 6)
V	cutting speed
	fundamental dimension (velocity) in dimensional analysis

	voltage
	volume in Weibull statistics
V_C	chip speed
V_W	velocity of work (Chapter 16)
V'	a volume
$V^{\#}$	cost optimum cutting speed
$V^{\#\#}$	production rate optimum cutting speed
V_{60}	60-min tool-life
V_{240}	240-min tool-life
W	weight
	limiting wattage for strain-gage
Y	flow (yield) stress in uniaxial tension
Z	nondimensional quantity in Chapter 12 = $(4\pi DK)/(Vt^2)$
a	radius of contact area in indentation hardness
	radius of neck of tensile specimen
	acceleration
	imperfection spacing (Chapter 6)
a'	tool face contact length
a_1, a_2	atomic spacings
b	width of cut (depth of cut in turning)
	slider width (Chapter 10)
	width of beam
	offset distance for chip breaker (Fig. 18.7)
b_C	deformed chip width
c	half-length of crack
	length of chisel edge of drill
d	diameter
	maximum depth of crater on tool face
e	nominal strain based on original gage length (l_o)
	EMF
	secondary cutting edge length (Chapter 14)
f	feed per revolution (drilling)
	feed per tooth (milling)
	width of flat in disc test
f_e	exciting frequency
g	acceleration due to gravity
	cost of cutting fluid additive per gallon (Chapter 19)
h	height of beam
	depth of heated layer (Chapter 10)
	height of scallop left on milled surface
	drop height in drop test
h_c	critical drop height for fracture
i	inclination angle
	electrical current
k	coefficient of thermal conductivity
	plane strain flow stress in shear
	Boltzmann's constant
l	length

	undeformed chip length
	axial length of cut in turning
	half-length of slider (Chapter 12)
l_C	deformed chip length
m	mass
	strain rate sensitivity index
	half-width of slider (Chapter 12)
	Weibull slope
n	strain hardening index
	exponent in Taylor tool-life equation
	number of cutter teeth
	number of revolutions
	number of planes per unit distance (Chapter 9)
p	pressure
	point half angle of drill
	normal stress at center of Mohr's circle in slip line field analysis
$\bar{p}$	mean pressure on punch face (Meyer hardness)
q	heat flux in Chapter 12 $[FL^{-2}T^{-2}]$
r	cutting ratio = t/t_C
	moment arm length
	nose radius of tool
t	undeformed chip thickness (feed in turning)
	time
	axial thickness in disc test
t_C	deformed chip thickness
t_m	maximum undeformed chip thickness (milling)
u	total cutting energy per unit volume
u_A	surface energy per unit volume
u_c	specific elastic tensile energy for fracture in impact
	fracture energy
u_F	friction energy per unit volume
u_M	momentum energy per unit volume
u_o	specific energy of thermal origin (Chapter 9)
u_S	shear energy per unit volume
w	extent of wear land on clearance face of tool
	web thickness of drill
	crack width
w_C	weight of chip
x	cost of machine, operator, and overhead per unit time
y	mean value of single cutting edge
y_o	initial displacement
Δy	thickness of shear plane
α	rake angle
	ferrite
	ship line coordinate direction
	fraction of A_R strongly bonded to mating surface
	angular deformation
α'	decrease in rake angle due to secondary shear (Fig. 3.20)

α_b	back rake angle
α_e	effective rake angle
α_n	normal rake angle
α_r	radial rake angle
α_s	side rake angle
α_v	velocity rake angle
β	friction angle on tool face = $\tan^{-1}(F_C/N_C)$
	slip line coordinate direction
β'	$\tan^{-1}(\tau/\sigma)$ on shear plane
γ	shear strain
γ'	specific weight of work material
$\dot{\gamma}$	time rate of shear strain
δ	linear deformation
	extent of secondary shear zone (Fig. 12.63)
	wedge angle of principal cutting edge (Fig. 10.14)
	inclination of free surface (Chapter 17)
	helix angle (drill)
ε	true (ln) strain
	feed angle of drill
ε_e	effective strain
ε_f	strain at fracture in chip (Chapter 18)
ε_U	strain at point of onset of necking = ultimate strain
ε_y	strain at yield point
$\varepsilon_1, \varepsilon_2, \varepsilon_3$	principal strains
ζ	setting angle
η	angle between tool face and plane of maximum shear stress (Fig. 8.3)
η'	angle between shear plane and plane of maximum shear stress
η_C	chip flow angle (Fig. 16.5)
η_S	shear flow angle [Eq. (16.8)]
θ	temperature (fundamental dimension in dimensional analysis)
	clearance angle
	angular extent of BUE (built-up edge)
	angle of twist in torsion test
	chip breaker face angle (Fig. 18.1a)
	cone half angle (for conical indentor or punch θ_e = effective cone half angle)
	angle in Fig. 8.4a
θ_f	workpiece surface temperature 180° from point of cutting
θ_e	end-relief angle
θ_m	maximum temperature
θ_o	ambient temperature of work (Chapter 12)
θ_o'	ambient temperature of tool (Chapter 12)
θ_s	side relief angle
$\bar{\theta}$	mean cutting temperature
$\bar{\theta}_S$	mean shear plane temperature (Chapter 12)
$\bar{\theta}_T$	mean temperature rise in cutting (Chapter 12)
$\bar{\theta}_t$	mean tool temperature by chip–tool thermocouple technique
$\Delta\bar{\theta}_F$	mean temperature rise on tool face (Chapter 12)
λ	chip compression ratio (reciprocal of cutting ratio = $1/r$)

μ	coefficient of tool-face friction = tan $\theta = F_C/N_C$
ν	Poisson's ratio
Π	nondimensional group in dimensional analysis
ρ	radius at tip of abrasive particle (Chapter 11)
	radius of curvature of tool tip
ρC	volume specific heat
σ	normal stress
σ_C	nominal uniaxial compressive stress at fracture
σ_c	critical tensile stress at fracture
	normal stress corrected for nonuniform stress in neck of tensile specimen
σ_D	nominal tensile stress in disc test at fracture
σ_e	effective normal stress
σ_f	normal stress at fracture
σ_{fo}	constant in Bridgman fracture equation
σ_H	mean principal stress ($\cong$ hydrostatic stress)
σ_0	characteristic stress in Weibull statistics
σ_x	elastic tensile stress at disc center in disc test
σ_y	elastic compressive stress at disc center in disc test
σ_T	nominal uniaxial tensile stress at fracture
σ_U	stress at onset of necking = ultimate stress
σ_{xD}	nominal tensile stress at center of disc at fracture
σ_{xT}	nominal tensile stress in uniaxial tensile test at fracture
$\sigma_1, \sigma_2, \sigma_3$	principal stresses ($\sigma_1 > \sigma_2 > \sigma_3$)
$\sigma_1', \sigma_2', \sigma_3'$	principal deviator stresses
$\bar{\sigma}$	mean normal stress
	effective normal stress
τ_0	theoretical shear strength
ϕ	shear angle
	angle of shear coordinate rotation in slip line field analysis
ϕ_n	normal shear angle (Chapter 16)
ψ	some function (in dimensional analysis)
	angle between shear plane and direction of maximum deformation in chip (Fig. 3.12)
ω	angular velocity (rad s^{-1})
	angle in Fig. 8.5
¢	total cost per part
¢*	optimum cost per part
¢#	optimum cost per cut
$^w/_o$	weight percent

CONTENTS

1 INTRODUCTION

There are several methods of changing the geometry of bulk material to produce a mechanical part:

1. by putting material together (+)
2. by moving material from one region to another (0)
3. by removing unnecessary material (–)

These operations may be performed on the atomic, micro, or macro scales. For example, electroplating and electroforming are plus operations at the atomic level while the fabrication of a structure by welding is a plus operation at the other end of the spectrum (macro joining). Rolling, forging, and extrusion are examples of (0) operations performed at the macro level while surface burnishing is at the micro level. Removal operations (–) with which this book is concerned are performed primarily at the macro level (cutting).

Another way of classifying operations is in terms of the temperature pertaining. Mechanical properties are related to the amplitude of vibration of adjacent atoms which varies linearly with absolute temperature. The melting point of a metal represents a critical temperature where the amplitude of atomic vibration is sufficient to cause a structural change from that of a solid to that of a liquid. At equal percentages of melting temperature on the absolute temperature scale, metals have similar properties and this suggests an homologous temperature (T_H) scale which corresponds to the fraction of the melting temperature on the absolute (K or R) temperature scale. Metals deformed below $T_H = 0.5$ behave differently than those deformed above $T_H = 0.5$. Deformation below $T_H = 0.5$ is called cold working and takes place primarily within individual crystals and is relatively strain rate insensitive but strongly strain sensitive (strain hardening). Deformation above $T_H = 0.5$ is called hot working, occurs primarily by grain boundary rearrangement, and is relatively strain rate sensitive but insensitive to strain (negligible strain hardening). Machining that occurs at temperatures above $T_H = 0.5$ is called hot machining. For example, steel has a melting temperature of about 1540 °C (2800 °F) or 1540 + 273 ≃ 1810 °K (or 2800 + 460 = 3260 °R). For hot machining, steel should be cut at an homologous temperature of at least $T_H = 0.5$ (or 630 °C or 1160 °F).

There are still other ways of classifying material removal operations that will be developed in subsequent chapters of this book.

Importance of Material Removal

The importance of material removal operations in the scheme of things may be realized by considering the total cost associated with this activity, including expendable tool cost, labor cost, and cost of capital investment. In the United States, the yearly cost associated with material removal has been estimated at about 10% of the gross national product.

The importance of the cutting process may be further appreciated by the observation that nearly every device in use in our complex society has one or more machined surfaces or holes.

There are several reasons for developing a rational approach to material removal:

1. to improve cutting techniques—even minor improvements in productivity are of major importance in high volume production
2. to produce products of greater precision and of greater useful life
3. to increase the rate of production and produce a greater number and variety of products with the tools available

All basic fields of industrial endeavor have taken similar paths in the course of their development. The earliest work has generally been carried out on a purely empirical basis and in many instances such activities have been highly developed by following the case method. While this method presents a clear picture of each specific job, a great many cases must be considered before sufficient examples have been presented to enable all common situations to be covered. This approach has been extensively used in metal cutting as well as in other fields, such as machine design, hydraulics, metallurgy, and even such nonengineering activities as law and medicine. The weakness of the method lies in its failure to provide a direct means for solving problems which lie beyond the range of current experience. Each new case that is established must be arrived at by a costly procedure of trial and error.

Not too many years ago, steam turbines and power machinery were designed largely in accordance with the judgement of the designer, rather than by following the more rational approach involving stress analysis that is in wide use today. Similarly, the design of hydraulic conduits and machinery that once was done by rule-of-thumb procedures is now being accomplished largely with the art of the principles of fluid mechanics. In the field of metallurgy, steelmaking is being carried out by considering it a special problem in physical chemistry instead of employing the age-old recipe technique. Metal cutting tools and procedures are still largely established by the old case method. This activity has resisted the impact of modern technology and the scientific method, mainly due to the complexity of the operations but also partly due to the attitude held toward metal cutting in engineering schools.

Traditionally, metal cutting has been part of the training of mechanical engineers. However, in the past, a trade-school approach was generally adopted, emphasis being placed entirely upon nomenclature, the mastery of machine manipulation, and the learning of a large number of disconnected empirical rules. In some instances, the major objective has actually been the production of trinkets, thus appealing to the hobby instincts of the student rather than developing the ability to apply fundamental concepts.

Approach to Subject

In this treatment of the subject we will consider the cutting process in fundamental terms. The objective is to explain a number of commonly observed results rather than to present a large mass of