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Advanced Machining Processes

NONTRADITIONAL and HYBRID MACHINING PROCESSES

- Water Jet Machining (WJM)
- Electrochemical Machining (ECM)
- Electro Discharge Machining (EDM)
- Hybrid Electrochemical Processes

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Nontraditional and Hybrid Machining Processes

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Dedicated to my wife Soaad El-Hofy

Preface

Machining processes produce finished products with a high degree of accuracy and surface quality. Conventional machining utilizes cutting tools that must be harder than the workpiece material. The use of difficult-to-cut materials encouraged efforts that led to the introduction of the nonconventional machining processes that are well-established in modern manufacturing industries.

Single-action nontraditional machining processes are classified on the basis of the machining action causing the material removal from the workpiece. For each process, the material removal mechanism, machining system components, process variables, technological characteristics, and industrial applications are presented.

The need for higher machining productivity, product accuracy, and surface quality led to the combination of two or more machining actions to form a new hybrid machining process. Based on the major mechanism causing the material removal process, two categories of hybrid machining processes are introduced. A review of the existing hybrid machining processes is given together with current trends and research directions. For each hybrid machining process the method of material removal, machining system, process variables, and applications are discussed.

This book provides a comprehensive reference for nontraditional machining processes as well as for the new hybrid machining ones. It is intended to be used for degree and postgraduate courses in production, mechanical, manufacturing, and industrial engineering. It is also useful to engineers working in the field of advanced machining technologies.

In preparing the text, I paid adequate attention to presenting the subject in a simple and easy to understand way. Diagrams are simple and self-explanatory. I express my gratitude to all authors of various books, papers, Internet sites, and other literature which have been referred to in this book. I will be glad to receive comments and suggestions for enhancing the value of this book in future editions.

Outline of the book

The following subjects and chapters are organized as a journey toward understanding the characteristics of nonconventional and hybrid machining processes. The book is written in eight chapters:

Chapter 1: Material Removal Processes
Chapter 2: Mechanical Processes
Chapter 3: Chemical Processes
Chapter 4: Electrochemical Processes
Chapter 5: Thermal Processes
Chapter 6: Hybrid Electrochemical Processes
Chapter 7: Hybrid Thermal Processes
Chapter 8: Material Addition Processes

In Chap. 1, the history and progress of machining is introduced. The difference between traditional and nontraditional machining is explained. Examples for conventional machining by cutting and abrasion are given. Single-action nontraditional machining is classified according to the source of energy causing the material removal process. Hybrid machining occurs as a result of combining two or more machining phases. Hybrid machining is categorized according to the main material removal mechanism occurring during machining.

Chapter 2 covers a wide range of mechanical nontraditional machining processes such as ultrasonic machining (USM), water jet machining (WJM), abrasive water jet machining (AWJM), ice jet machining (IJM), as well as magnetic abrasive finishing (MAF). In these processes the mechanical energy is used to force the abrasives, water jets, and ice jets that cause mechanical abrasion (MA) to the workpiece material.

In Chap. 3, the chemical machining processes such as chemical milling (CHM), photochemical machining (PCM), and electrolytic polishing (EP) are discussed. In these processes the material is mainly removed through chemical dissolution (CD) occurring at certain locations of the workpiece surface.

Chapter 4 deals with electrochemical machining (ECM) and related applications that include electrochemical drilling (ECDR), shaped tube electrolytic machining (STEM), electrostream (ES), electrochemical jet drilling (ECJD), and electrochemical deburring (ECB). The electrochemical dissolution (ECD) controls the rate of material removal.

Machining processes that are based on the thermal machining action are described in Chap. 5. These include electrodischarge machining (EDM), laser beam machining (LBM), electron beam machining (EBM), plasma beam machining (BPM), and ion beam machining (IBM). In most of these processes, material is removed from the workpiece by melting and evaporation. Thermal properties of the machined parts affect the rate of material removal.

Hybrid electrochemical machining processes are dealt with in Chap. 6. Some of these processes are mainly electrochemical with mechanical assistance using mechanical abrasion such as electrochemical grinding (ECG), electrochemical honing (ECH), electrochemical superfinishing (ECS), and electrochemical buffing (ECB). The introduction of ultrasonic assistance enhances the electrochemical dissolution action during ultrasonic-assisted ECM (USMEC). Laser beams activate electrochemical reactions and hence the rate of material removal during laser-assisted electrochemical machining (ECML).

Chapter 7 covers the hybrid thermal machining processes. Electrochemical dissolution (ECD) enhances the electrodischarge erosion action (EDE) during electroerosion dissolution machining (EEDM). Mechanical abrasion encourages the thermal erosion process during electrodischarge grinding (EDG) and abrasive-assisted electrodischarge machining (AEDG and AEDM). Ultrasonic assistance encourages the discharging process during ultrasonic-assisted EDM (EDMUS). Triple-action hybrid machining occurs by combining both electrochemical dissolution (ECD) and mechanical abrasion to the main erosion phase during electrochemical discharge grinding (ECDG).

Material addition processes are covered in Chap. 8. These include a wide range of rapid prototyping techniques that are mainly classified as liquid-, powder-, and solid-based techniques.

Advantages of the book

1. Covers both the nonconventional and hybrid machining processes
2. Classifies the nonconventional machining processes on the basis of the machining phase causing the material removal (mechanical, thermal, chemical, and electrochemical processes)
3. Classifies the hybrid machining processes based on the major mechanism and hence the machining phase causing the material removal from the workpiece into hybrid thermal and hybrid electrochemical processes
4. Presents clearly the principles of material removal mechanisms in nonconventional machining as well as hybrid machining
5. Explains the role of each machining phase (causing the material removal) on the process behavior
6. Describes the machining systems, their main components, and how they work

7. Discusses the role of machining variables on the technological characteristics of each process (removal rate, accuracy, and surface quality)
8. Introduces the material addition processes that use the same principles adopted in material removal by nonconventional processes

This book is intended to help

1. Undergraduates enrolled in production, industrial, manufacturing, and mechanical engineering programs
2. Postgraduates and researchers trying to understand the theories of material removal by the modern machining processes
3. Engineers and high-level technicians working in the area of advanced machining industries

Why did I write the book?

This book presents 28 years of experience including research and teaching of modern machining methods at many universities around the world. My career started early in the academic year 1975–1976 through a senior project related to the effect of some parameters on the oversize of holes produced by ECM. Afterward, I finished my M.S. degree in the field of accuracy of products by electrolytic sinking in the Department of Production Engineering at Alexandria University. As an assistant lecturer I helped to teach about conventional and nonconventional machining.

I spent 4 years on a study leave in the U.K. working toward my Ph.D. at Aberdeen University and 1 year at Edinburgh University. During that time I finished my thesis in the field of hybrid electrochemical arc wire machining (ECAM) under the supervision of Professor J. McGeough. That work was supported by the Wolfson Foundation and the British Technology Group. I had the Overseas Research Student (ORS) award for three successive years which supported me during my research work. Working on a large research team and sharing discussions in regular meetings, I gained more experience related to many advanced and hybrid machining applications such as hybrid ECM-EDM, ECAM drilling, and electrochemical cusp removal. I was a regular steering committee member for the CAPE conference organized by Professor McGeough. I edited two chapters and shared in the writing of chapter 1 of his book *Micromachining of Engineering Materials*.

Throughout my academic career in which I started out as a lecturer and moved up to being a full professor of modern machining processes, I have taught all subjects related to machining in many universities around the world. I have published about 50 research papers related to nonconventional as well as hybrid machining processes. During my work in Qatar University I was responsible for teaching the advanced machining techniques course. Collecting all materials that I had in a book therefore came to my mind. I have been working on this task since the year 2001.

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List of Acronyms

Abbreviation	Description
AEDG	Abrasive electrodischarge grinding
AEDM	Abrasive electrodischarge machining
AFM	Abrasive flow machining
AJM	Abrasive jet machining
AWJM	Abrasive water jet machining
BHN	Brinell hardness number
BIS	Beam interference solidification
BEDMM	Brush erosion dissolution mechanical machining
BPM	Ballistic particles manufacturing
C	Cutting
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CAPP	Computer-assisted process planning
CBN	Cubic boron nitride
CD	Chemical dissolution
CHM	Chemical milling
CIM	Computer-integrated manufacturing
CVD	Carbon vapor deposition
CNC	Computer numerical control
CW	Continuous wave
EBM	Electron beam machining
ECAM	Electrochemical arc machining
ECB	Electrochemical buffing
ECD	Electrochemical dissolution
ECDB	Electrochemical deburring
ECDG	Electrochemical discharge grinding

Abbreviation	Description
ECDM	Electrochemical discharge machining
ECDR	Electrochemical drilling
ECG	Electrochemical grinding
ECH	Electrochemical honing
ECJD	Electrochemical jet drilling
ECM	Electrochemical machining
ECML	Laser-assisted electrochemical machining
ECS	Electrochemical superfinishing
EDE	Electrodischarge erosion
EDG	Electrodischarge grinding
EDM	Electrodischarge machining
EDMUS	Electrodischarge machining with ultrasonic assistance
EDT	Electrodischarge texturing
EEDM	Electroerosion dissolution machining
EP	Electropolishing
ES	Electrostream
FDM	Fused deposition modeling
FJ	Fluid jet
G	Grinding
HAZ	Heat-affected zone
HF	Hone forming
HIS	Holographic interference solidification
IBM	Ion beam machining
IJM	Ice jet machining
LAE	Laser-assisted chemical etching
LAJECM	Laser-assisted jet ECM
LAN	Local area network
LBM	Laser beam machining
LBT	Laser beam texturing
LENS	Laser engineered net shaping
LOM	Laminated object modeling
LTP	Liquid thermal polymerization
MA	Mechanical abrasion
MAF	Magnetic abrasive finishing
MJM	Multijet modeling
MMC	Metal matrix composites
MPEDM	Mechanical pulse electrodischarge machining

Abbreviation	Description
MRR	Material removal rate
MS	Mechanical scrubbing
MUSM	Micro-ultrasonic machining
NC	Numerical control
ND-YAG	Neodymium-doped yitrium-aluminum-garnet
PAM	Plasma arc machining
PBM	Plasma beam machining
PCB	Photochemical blanking
PCD	Polycrystalline diamond
PECM	Pulse electrochemical machining
PF	Photoforming
PCM	Photochemical milling
PM	Pulsed mode
RP	Rapid prototyping
RUM	Rotary ultrasonic machining
SB	Shot blasting
SDM	Shape deposition manufacturing
SFF	Solid free-form fabrication
SFP	Solid foil polymerization
SGC	Solid ground curing
SLA	Stereolithography
SLS	Selective laser sintering
STEM	Shaped tube electrolytic machining
TEM	Thermal energy method
US	Ultrasonic
USM	Ultrasonic machining
USMEC	Ultrasonic-assisted electrochemical machining
VRR	Volumetric removal rate
WJM	Water jet machining

List of Symbols

Symbol	Definition	Unit
a	tool feed rate	mm/min
A	atomic weight	
A/Z	chemical equivalent	g
$A/Z.F$	electrochemical equivalent	g/C
A_b	area of laser beam at focal point	mm^2
C	electrochemical machining constant	mm^2/s
C/y_e	metal removal rate per unit area	mm/min
C_d	diametrical overcut	mm
C_l	constant depending on material and conversion efficiency	
C_s	speed of sound in magnetostrictor material	m/s
d	CHM undercut	mm
D	EDM depth	mm
D/L_c	corner wear ratio	mm
D/L_e	end wear ratio	
D/L_s	side wear ratio	
d/T	etch factor	
d_a	mean diameter of abrasive particles	μm
d_b	beam diameter at contact with workpiece (slot width)	mm
d_s	spot size diameter	mm
d_t	tool diameter	mm
d_w	produced hole diameter	mm
dy/dt	workpiece rate of change of position	mm/min
E	Young's modulus	MPa
ϵ_m	coefficient of magnetostriction elongation	

Symbol	Definition	Unit
E_m	magnitudes of magnetic energy	
e_v	number of pulses	
E_v	vaporization energy of material	W/mm^3
E_w	magnitudes of mechanical energy	
$\mathcal{F}$	frequency of oscillation	Hz
f	frequency of changes in magnetic field	Hz
F	Faraday's constant	C/g per-ion
F_l	focal length of lens	cm
f_p	frequency of pulses	Hz
f_r	resonance frequency	Hz
g	depth of hole required	
g_e	depth of hole removed per pulse	mm
g_w	wheel-workpiece gap	
h	thickness of material	mm
H	magnetic field intensity	
H_0	surface fracture strength	BHN
$H_{\rm rms}$	surface roughness	µm
H_w	hardness of workpiece material	N/mm^2
i	EDM current	A
I	electrolyzing current	A
I_e	beam emission current	mA
I_p	pulse current	A
J	current density	A/mm^{-2}
K	constant	
K_h	constant	µm/µJ
K_m	coefficient of magnetomechanical coupling	
K_p	coefficient of loss	
l	original length of magnetostrictor	
L	slot length	mm
L_c	corner wear	mm
L_e	end wear	mm
L_p	laser power	W
L_s	side wear	mm
m	amount of mass dissolved	g
n	density of target material	atoms per cm^3
n_e	number of pulses	
N	number of abrasives impacting per unit area	

Symbol	Definition	Unit
N_M	relative machinability	
P	density of magnetostrictor material	kg/m^3
P_d	power density	W/cm^2
P_r	pulse power	W
q_c	specific removal rate for pure metals	mm^3/(min·A)
Q_{ECD}	removal rate of electrochemical dissolution	mm^3/min
Q_{ECG}	total removal rate in ECG	mm^3/min
Q_l	linear removal rate	mm/min
Q_{MA}	removal rate of mechanical abrasion	mm^3/min
Q_v	volumetric removal rate	mm^3/min
R	mean radius of grit	mm
R_a	average roughness	μm
R_t	maximum peak to valley roughness	μm
R_w	wear ratio	
S	static stress on tool	kg/mm^2
$s(\theta)$	IBM yield	atoms per ion
t	machining time	min
T	CHM depth of cut	mm
t_i	pulse interval	μs
t_m	machining time	
t_p	pulse duration	μs
T_r	ratio of workpiece to tool electrode melting points	
T_t	melting point of tool electrode	°C
T_w	melting point of workpiece material	°C
U	mean velocity	
V	gap voltage	V
$V(\theta)$	etch rate	atoms per min/ mA cm^2
V_a	beam accelerating voltage	kV
V_e	volume of electrode consumed	mm^3
V_g	grinding wheel penetration speed	mm^3/min
VRR	material removal rate	mm^3/min
V_s	machining rate	mm^2/min
V_w	volume of workpiece removed	mm^3
V_w / V_e	volume wear ratio	
W	pulse energy	μJ