The success of any new engineering process depends greatly on the efforts made towards understanding its principles. In the case of electrochemical machining (ECM), the nature of the process has meant that these efforts lie in several fields which are not necessarily related: for instance, fluid dynamics and applied electrochemistry and mathematics. In consequence, both the engineer and research specialist are confronted with difficult tasks. The former, carrying the eventual responsibility for making ECM practicable, must take into account the appropriate features of all relevant fields, while the problems facing the engineer have to be appreciated by the latter.

This book makes a contribution to overcoming these problems firstly, by correlating the significant features of those fields which have a part in ECM and secondly, by discussing recent advances. Throughout the book, typical calculations are carried out, and at the end of each chapter there is a bibliography and/or a reference list.

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Principles of Electrochemical Machining

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Preface

The nature of the electrochemical machining process has meant that the efforts made towards understanding its principles lie in several different fields. Although increasing light on the subject continues to be shed by studies in these separate disciplines, the engineer still carries the problem of making judgements which embrace the entire process. He should, therefore, be conversant with the appropriate features of all the relevant fields.

The purpose of this book is to contribute towards overcoming this problem by describing and correlating those aspects of the relevant fields which have proved useful in engineering studies of electrochemical machining. To that end, the first three chapters are devoted to a discussion of the developments which have led to the need for electrochemical machining, and the fluid dynamic and electrochemical principles on which the process is based. It is recognised that specialists in these two main fields may regard the treatment of their subjects as elementary, but they will probably accept that these topics are not necessarily closely related, and that acquaintance with both is necessary in electrochemical machining work. The contents of each of these chapters can be studied in greater detail with the help of the bibliography given at the end of the chapters. In the fourth chapter, the characteristics of metals electrochemically machined in different electrolytes are examined in the light of established and recent theories. Chapter 5 deals with the dynamics and kinematics of the process. The sixth and seventh chapters are concerned with the fundamental problems of the process, namely, the prediction of the change of anode shape with machining time, and the design of cathode tool shapes to machine an anode workpiece to a specified form. In the final chapter, the principles of the process described in the preceding chapters are illustrated by examples from industrial practice. Throughout the book, calculations are carried out at appropriate stages to give the reader a grasp of the physical dimensions of the quantities involved in the process. Although SI units have been preferred, the character of the subject has not easily lent itself towards the exclusive use of this system. Accordingly, some quantities are given in other metric units which are in common use.

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Contents

Principal Notation

a	Tafel constant [= $(-2.303RT/z\alpha F)\log J_0$]
a	length of mesh 'arm' (Chapter 7)
a, $[a]$	activity, activity term
a_n	Fourier coefficient (Chapter 6)
A	electrode area (Chapter 1)
A	atomic weight
A	logarithmic throwing index (Chapter 4)
A	cross-section area of flow channel (Chapter 2)
A	dimensionless process quantity (= $\rho_0 e_g/\sigma\rho_g e_a$) (Chapter 5)
b	Tafel constant (= $2.303RT/z\alpha F$)
b	width of electrode
b_n	Fourier coefficient (Chapter 6)
B	dimensionless process quantity (= ζT_r) (Chapter 5)
$c(y)$	ion concentration (particle numbers per unit volume of solution) (Chapter 3)
c_e	specific heat of electrolyte
c_n	Fourier coefficient (Chapter 6)
C	concentration of electrolyte solution
C	wetted perimeter (Chapter 2)
C_b	bulk concentration of reacting species (Chapters 3, 4, 5)
C_H	hydrogen ion concentration
C_S	interfacial concentration of dissolution products
C	dimensionless process quantity [= $(2/\sigma)(e_g/e_a)(RT_0/U_0^2)$] (Chapter 5)
d	pipe diameter
d_h	hydraulic diameter
d_n	Fourier coefficient (Chapter 6)

D	diffusion coefficient
e	electron charge
e_a	electrochemical equivalent of anode metal
e_g	electrochemical equivalent of gas
E	reversible electrode potential
E	electric field (Chapter 7)
E_δ	electric field across diffusion layer (Chapter 3)
E_0	normal electrode potential (Chapter 3)
f	activity coefficient (Chapter 3)
f	coefficient of frictional resistance (Chapter 2)
f	electrode (cathode) feed-rate
$f(J)$	arbitrary current density-dependent function of cathode overpotential (Chapters 4, 5, 6)
F	Faraday's constant (96 500 C)
F	gravitational force (Chapter 2)
$g(J)$	arbitrary current density-dependent function of anode overpotential (Chapter 6)
h	inter-electrode gap width
$h_a(x)$	local width of layer of anodic products (Chapter 5)
h_e	equilibrium gap width
$h_{el}(x)$	local width of central layer of pure electrolyte (Chapter 5)
$h_g(x)$	local width of layer of hydrogen gas bubbles (Chapter 5)
h_0	equilibrium gap width at gap inlet
h_∞	total overcut (Chapter 7)
$h(t)$	width of gap at machining time, t
$h(0)$	width of gap at start of machining, $t = 0$
H_g	volume of hydrogen produced per coulomb (Chapter 4)
i	unit vector in x direction (Chapter 2)
i	square root of (-1) (Chapter 7)
(i, j)	general coordinates of grid points (Chapter 7)
I	current
j	unit vector in y direction (Chapter 2)
j	number flux of ion particles (Chapter 3)
J	current density
J_l	limiting current density (Chapters 3, 4, 5)
J_0	exchange current density
J_p	passivation current density
$\bar{J}$	a defined average current density, consequence of overpotential (Chapters 4, 6)
k	Boltzmann's constant

k	wave number
$\mathbf{k}$	unit vector in z direction (Chapter 2)
K_0	pressure loss coefficient for rectilinear gap without ECM (Chapter 5)
K_s	activity solubility product (Chapter 3)
l	characteristic length for flow path (Chapter 2)
l	half-width of cathode (Chapter 7)
L	electrode length
L	linear ratio (Chapter 4)
m	mass of metal removed, or deposited
$\dot{m}$	rate of metal removal
m_a	local mass flux rate for anodic products (mass per unit time per unit area) (Chapter 5)
m_g	local mass flux rate for hydrogen gas (Chapter 5)
M	metal distribution ratio (Chapter 4)
M	machining parameter ($= A\kappa_e/z\rho_a F$)
M	frictional pressure drop multiplier for two-phase flow
n	number of particles with energy to cross interface (Chapter 3)
n_e	electrochemical valency
n_t	total number of particles (Chapter 3)
N	Avogadro's number (6×10^{23})
Nu	Nusselt number
$\mathrm{Nu_p}$	Nusselt number associated with passivation
p	pressure
$p(t)$	mean gap between electrodes (Chapters 4, 5, 6, 7)
p_e	mean equilibrium gap (Chapters 4, 6)
$p(0)$	mean gap between electrodes at time $t = 0$ (Chapter 6)
pH	negative logarithm of hydrogen ion concentration
$\mathbf{P}$	boundary force (Chapter 2)
Q	volumetric flow-rate
$\mathbf{r}_a$	vector function of anode position
$\dot{\mathbf{r}}_a$	dissolution rate of anode (Chapters 6, 7)
R	Gas Constant
R	radius of pipe (Chapter 2)
R	residual (Chapter 7)
R	resistance (Chapter 1)
Re	Reynolds number
S	dimensionless process quantity ($= \rho_0 h_0 U_0/L\rho_a f$) (Chapter 5)

Sc	Schmidt number ($= \nu/D$)
t	time of machining
t_+, t_-	cationic, anionic transport number (Chapter 3)
T	temperature
T	throwing power (Chapter 4)
T_b	boiling temperature
T_r	reference temperature ($= V/e_a c_e$) (Chapter 5)
u	electrolyte velocity in x direction
u_f	friction velocity
u_+	cationic mobility (Chapter 3)
u_-	anionic mobility (Chapter 3)
u_{max}	maximum electrolyte velocity
$\bar{u}$	mean electrolyte velocity
U	mainstream electrolyte velocity
$\mathbf{U}$	electrolyte velocity vector (Chapter 2)
U_a	local velocity of layer of anodic products (Chapter 5)
U_e	local velocity of layer of pure electrolyte (Chapter 5)
U_g	local velocity of layer of gas (Chapter 5)
v	electrolyte velocity in y direction
$\dot{v}$	volumetric rate of metal removal
V	applied potential difference (voltage)
V_{rms}	applied voltage (alternating current conditions) (Chapter 5)
w	electrolyte velocity in z direction (Chapter 2)
W	uninsulated land width (Chapter 7)
$W_{1,2}$	energy required to pass interface from metal to solution (subscript 1) and vice versa (subscript 2)
x	coordinate distance along electrode length
x	number of cations (Chapter 3)
x_E	entry length (Chapter 2)
(x, y, z)	coordinate system
X_i	percentage by weight of element i (Chapter 4)
y	coordinate distance from cathode to anode, normal to x direction
y	number of anions (Chapter 3)
z	transverse direction to (x, y) axes
z	valency
z_+	charge on cations (Chapter 3)
z_-	charge on anions (Chapter 3)
α	degree of dissociation (Chapter 3)

α	fraction of overpotential contributing towards dissolution
α	void fraction
α	average cathode overpotential function $[= f(\bar{J})]$ (Chapters 4, 5, 6)
β	cathode overpotential function $[= \partial f(J)/\partial J]$ (Chapters 4, 6, 7)
γ	dimensionless process constant $(= h_0 U_0/Lf)$ (Chapter 5)
γ	anode overpotential function $[= g(J)]$ (Chapter 6)
Γ	current efficiency (Chapter 5)
δ	diffusion layer thickness
$\bar{\delta}$	average value of diffusion layer thickness
δ_d	displacement thickness (Chapter 2)
δ_g	width of layer containing electrolyte and gas bubbles
δ_0	thickness of laminar boundary layer
δ_l	thickness of viscous sub-layer
δ_t	thickness of turbulent boundary layer
ΔG	free energy change (Chapter 3)
ΔV	sum of overpotentials and reversible potentials at both electrodes
ϵ_{adm}	admissible height of surface projections (Chapter 2)
$\epsilon(t)$	amplitude (height) of surface irregularities
$\epsilon(0)$	initial value of amplitude of surface irregularities $(t = 0)$
ζ	temperature coefficient for electrolyte conductivity
η_a	activation overpotential
η_{conc}	concentration overpotential
η_r	resistance overpotential
θ	momentum thickness (Chapter 2)
θ	angle between normal to anode boundary and direction of cathode movement (Chapter 7)
κ_e	electrolyte conductivity
κ_0	electrolyte conductivity at gap inlet
κ_m	mean conductivity of electrolyte–gas medium
2λ	fundamental wavelength of anode irregularities
λ_+	defined quantity $(= Fu_+)$ (Chapter 3)
λ_-	defined quantity $(= Fu_-)$ (Chapter 3)
Λ_c	equivalent conductivity (Chapter 3)
Λ_m	molar conductivity
Λ_0	equivalent conductivity at very low limiting concentration
μ	absolute viscosity (Chapter 2)
μ	dimensionless overpotential parameter $(= \beta\kappa_e/\lambda)$
ν	kinematic viscosity
(ξ, η)	coordinate system in ζ-plane (Chapter 7)

ρ	resistivity (Chapter 1)
ρ_a	anode metal density
ρ_e	electrolyte density
ρ_g	gas density
σ	slip ratio $(= U_g/U_e)$ (Chapter 5)
σ	dimensionless configuration parameter $(= p/\lambda)$
τ	anode overpotential function $[= \partial g(J)/\partial J]$ (Chapter 6)
τ	machining constant (Chapter 7)
τ	shearing stress (Chapter 2)
τ_0	shearing stress at wall (Chapter 2)
ϕ	potential
$\partial\phi/\partial n$	normal component of electric field at anode surface
$\partial\phi/\partial s$	defined potential gradient along edge of conducting paper (Chapter 7)
ψ	thermionic work function (Chapter 3)
ψ	nondimensional process function $\{= fh(0)/[A\kappa_e(V - \Delta V)/zF\rho_a]\}$ (Chapter 5)
$(\psi_1 - \psi_2)$	contact potential difference (Chapter 3)
ω	overpotential parameter (Chapters 4, 6)
Ω	slip ratio $(= U_a/U_e)$ (Chapter 5)
Ω_1, Ω_2	characteristic parameter for equilibrium dissolution, deposition reaction (Chapter 3)

Subscripts

a	property of anode
c	property of cathode
e	property of electrolyte
$(h_e$	equilibrium gap width)
g	property of gas
m	property of metal (Chapter 3)
0	condition at gap inlet
+, –	property of positive, negative electrolyte ions (Chapter 3)

(Other subscripts defined in text)

Superscripts

0	dimensionless process variable
*	dimensionless quantity (Chapter 5)