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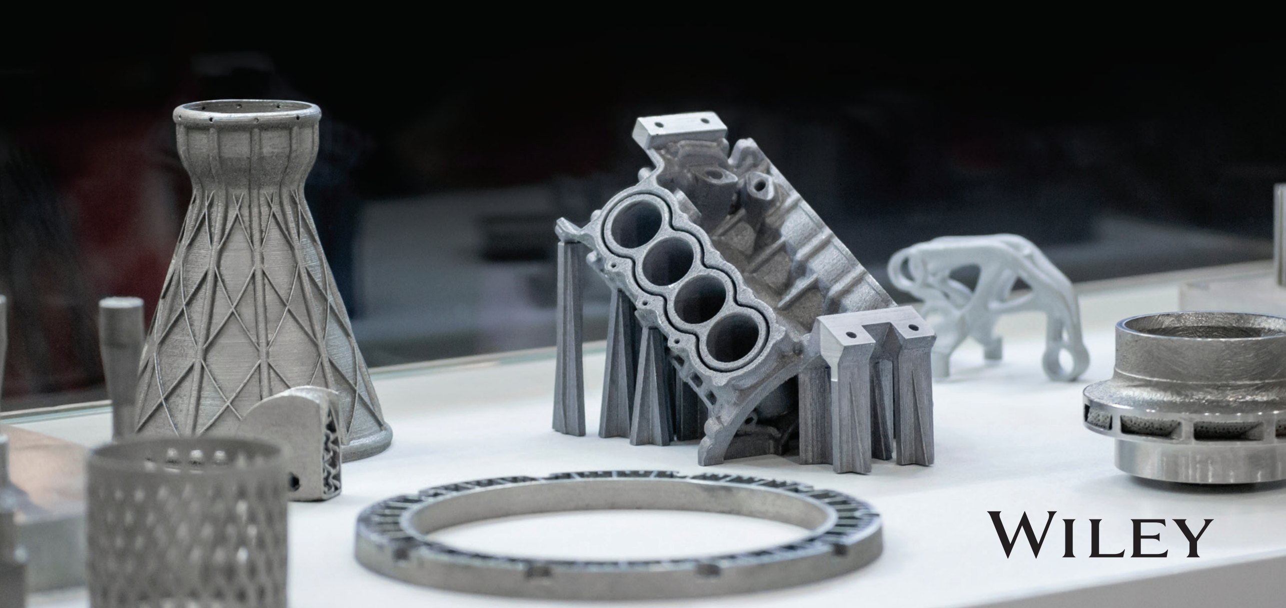
METAL ADDITIVE MANUFACTURING



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Ehsan Toyserkani, Dyuti Sarker, Osezua Obehi Ibhadode, Farzad Liravi, Paola Russo, Katayoon Taherkhani

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In memory of

Professor Pearl Sullivan (1961–2020)

Former Dean of Faculty of Engineering, University of Waterloo, Canada

A true leader, an exemplary advocate for engineering education, and a great friend

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Preface

Additive manufacturing (AM) promises to change the entire manufacturing enterprise over the next two decades. No longer limited to prototyping and low-volume manufacturing, AM is being adopted for *economies of scale* without compromising *economies of scope*. The need for the digitization of manufacturing, on-demand personalized manufacturing, distributed production, and rapid production in the event of crises have all elevated the position of AM in the medical and engineering sectors. AM is now a major research target for industrialized countries as they seek to regain leadership in advanced manufacturing through innovation. The global economy is on the verge of the next industrial revolution and sector after sector is pulling away from traditional, conventional production methods to engage in and utilize AM. However, this promise does come with many challenges, particularly for metal AM. Research and development activities are progressing at full steam to address multiple technical challenges, such as speed and productivity, quality assurance, standards, and end-to-end workflow.

A major skill sets gap currently hinders efforts to tackle these challenges. For companies seeking to embrace AM, this gap translates into a limited availability of expertise to draw an entry strategy to the AM industry. The wider adoption of AM will require overcoming the limited foundational understanding of AM that currently exists within the workforce. A thorough understanding of AM capabilities is necessary for technical experts to accurately communicate the pros and cons of AM to decision-makers, while preventing misconceptions and misinformation about AM capabilities. Currently, the knowledge gap is significantly impacting progress in the sector, as companies have difficulties in recruiting AM experts to help them develop effective designs for AM as well as meaningful business cases for metal AM.

This book is designed to help academia and industry move toward filling this gap. Enhancing AM skills will require the development of foundational knowledge of AM starting at the undergraduate level. To our knowledge, there is currently no textbook available that links the basics of fundamental undergraduate Engineering courses with metal AM processes. There is a clear need to customize undergraduate concepts in technical courses related to design, heat transfer, fluid mechanics, solid mechanics, and control, with respect to AM applications. Additionally, business- and management-oriented courses should include AM to facilitate the consideration of AM in conjunction with life cycle assessment and business model developments among students.

The development of this book was motivated by our desire to provide foundational material for a core undergraduate course in Mechanical and Manufacturing Engineering, and we envision its use in graduate courses as well. Universities globally are revising their curriculum to incorporate AM-related courses. This textbook may provide an introductory platform to be adopted in such courses to promote an appreciation for and grasp of AM among both undergraduate and graduate students. This book may also fill a gap for engineers working outside academia who want to appreciate AM processes by identifying links between traditional core physics and engineering concepts courses and AM. The book provides a step-by-step understanding of metal AM and a solid foundation of the topic for readers, who will subsequently be well equipped to explore AM research in greater depth.

For a broad range of readers, this book sheds light on various key metal AM technologies, focusing on basic physics and modeling. This textbook is not a literature survey, nor is it intended for readers with no engineering background. In contrast, it is an introduction to basic physical concepts and phenomena of metal AM processes and their applications. Relevant foundational concepts, such as energy deposition, powder bed fusion, and binder jetting processes, are explained in-depth and illustrated by case studies throughout the book. Additionally, two emerging processes for metal AM: material extrusion and material jetting, are described. Basic design for AM (DfAM) and quality assurance principles are also covered.

We would like to express our sincere gratitude to several people who helped in the preparation of this book. Special thanks to Francis Dibia, Ali Keshavarzkermani, Zhidong Zhang, Yuze Huang, Mazyar Ansari, Andrew Barlow, Misha Karpinska, Donovan Kwong, and Eniife Elebute, who helped us with some materials and produced some of the figures, as attributed in the book. In addition, we acknowledge all organizations, publishers, authors, and companies that permitted use of their figures, plots, and texts; they have been cited accordingly throughout the book. Last but not least, thanks to our families, who make it all worthwhile.

Like any first edition, this textbook may contain errors and typos. We openly welcome the reader's suggestions to be considered in the second edition of this textbook in which multiple problem sets for each chapter will be introduced.

January 2021 Ehsan Toyserkani, Dyuti Sarker, Osezua Obehi Ibhadode, Farzad Liravi, Paola Russo, Katayoon Taherkhani
Waterloo, Ontario, Canada

Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
3DQCN	Three-Dimensional Quasi-Continuous Network
AI	Artificial Intelligence
AE	Auto-Encoder
Al	Aluminum
AL	Absolute Limits
ALE	Arbitrary Lagrangian–Eulerian
AM	Additive Manufacturing
AMCs	Aluminum Matrix Composites
AMF	Additive Manufacturing File Format
AMGTA	Additive Manufacturer Green Trade Association
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ANSI	American National Standards Institute
APG	Absorptivity Profile Group
ASCII	American Standard Code For Information Interchange
ASTM	American Society for Testing and Materials
BD	Big Data
BESO	Bidirectional Evolutionary Structural Optimization
BJ	Binder Jetting
BJP	Binder Jet Printing
BP	Backpropagation
BSE	Backscattered Electrons
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAGR	Compound Annual Growth Rate
CAM	Computer-Aided Manufacturing

CCD	Charged-coupled device
CCT	Continuous Cooling Transformation
CDA	Constant Drawing Area
CET	Columnar-to-Equiaxed Transition
CFD	Computational Fluid Dynamics
CL	Cathodoluminescence
CMOS	Complementary Metal-Oxide Semiconductor
CNC	Computer Numerical Control
CNN	Convolutional Neural Network
COLIN	Convex Linearization
CS	Crack Susceptibility
CT	Computed Tomography
μCT	micro Computed Tomography
CVD	Chemical Vapor Deposition
CW	Continuous Wave
DAE	Differential-Algebraic Equation
DBN	Deep Belief Network
DC	Direct Current
DDA	Decreasing Drawing Area
DED	Directed Energy Deposition
DEM	Discrete/Dynamic Element Model
DfAM	Design for AM
DfM	Design for Manufacturing
DHA	Dust Hazard Analysis
DL	Deep Learning
DMLS	Direct Metal Laser Sintering
DoD	Drop-on-Demand
DoG	Difference of Gaussian
DXF	Drawing Exchange Format
EA	Electrical Arc
EAM	Embedded-Atom Method
EB	Electron Beam
EBAM	Electron Beam Additive Manufacturing
EB-DED	Electron Beam Directed Energy Deposition
EBF3	Electron Beam Freeform Fabrication
EBF^3	Electron Beam Fusion
EBM	Electron Beam Melting
EB-PBF	Electron Beam Powder Bed Fusion
EDM	Electrical Discharge Machining
EIGA	Electrode Induction Melting Inert Gas Atomization
EKF	Extended Kafman Filter
ELT	Effective Layer Thickness
EMFs	Electric and Magnetic Fields
ESO	Evolutionary Structural Optimization
FBG	Fiber Bragg Gratings
FCC	Face Centered Cubic
FCM	Finite Cell Method
FDM	Fused Deposition Modeling
FE	Finite Element
FEA	Finite Element Analysis

FEG	Field-Emission Gun
FEM	Finite Element Method
FFT	Fast Fourier Transformation
FGM	Functionally Graded Material
FGSs	Functionally Graded Structures
FIS	Fuzzy Inference System
FMC	Ford Motor Company
FN	False Negative
FP	False Positive
FS	Free Surface
GD	Gradient Descent
GM	General Motors
GMG	Geometrically Modified Group
GP	Gaussian Process
HA	Hydroxyapatite
HAZ	Heat-Affected Zone
HDR	Heating Depth Ratio
HF	Highly Filled
HIP	Hot Isostatic Pressing
HPM	Heaviside Projection Method
ICI	Inline Coherent Imaging
IDAM	Industrialization and Digitization of Additive Manufacturing
IDT	Interdigitated Transducers
IN	Inconel
IoT	Internet of Things
ISO	International Standards Organization
ISO	International Standards Organization
KF	Kafman Filter
KNN	K-nearest neighbors
LaB_6	Lanthanum Hexaboride
LBM	Lattice–Boltzmann Method
LCA	Life Cycle Assessment
LCF	Low Cycle Fatigue
LDED	Laser Directed Energy Deposition
LENS	Laser Engineered Net Shaping
LGA	Lattice Gas Automata
LM	Levenberg–Marquardt
LN	Large Negative
LoF	Lack of Fusion
LP	Large Positive
LPBF	Laser Powder Bed Fusion
LPM	Laser Power Monitoring
LSF	Level Set Functions
LSM	Level Set Method
LWIR	Long Wave Infrared
MAPE	Mean Absolute Prediction Error
MC	Metal Carbide
MD	Molecular Dynamics
ME	Material Extrusion
MG	Metallic Glass

MJ	Material Jetting
MMA	Method of Moving Asymptotes
MMCs	Metal Matrix Composites
MME	Metal Material Extrusion
MMP	Micro-Machining Process
MMV	Moving Morphable Voids
MOV	Main Oxidizer Valve
MPC	Metal–Polymer Composite
MPE	Maximum Permissible Exposure
MPM	Melt Pool Monitoring
MS	Multi-Speed
MSDS	Material Safety Data Sheet
MSE	Mean Squared Error
MTPS	Multifunctional Thermal Protection System
Nd	Neodymium
NDT	Non-Destructive Testing
NFPA	National Fire Protection Association
nHA	Nano-Hydroxyapatite
NHZ	Nominal Hazard Zone
Ni	Nickle
NIR	Near-Infrared
NIST	National Institute of Standards and Technology
NN	Neural Network
NS	Navier–Stokes
OCM	Optimality Criterial Method
OCT	Optical Coherence Tomography
OEM	Original Equipment Manufacturers
OPD	Optical Penetration Depth
OTLs	Orthogonal Translational Lattices
PBF	Powder Bed Fusion
PCA	Principal Component Analysis
PDF	Point Distribution Function
PF	Powder-Fed
PI	Proportional–Integral
PID	Proportional–Integral–Derivative
PMC	Polymer Matrix Composite
PMZ	Partially Melted Zone
PPE	Personal Protective Equipment
PPHT	Post-Processing Heat Treatment
PREP	Plasma Rotate Electrode Process
PSD	Particle Size Distribution
PTA-DED	Plasma Transferred Arc Directed Energy Deposition
PVD	Physical Vapor Deposition
PW	Pulsed Wave
PZT	Piezoelectric
R&D	Research and development
RAMP	Rational Approximation of Material Properties
RDM	Relative Density Mapping
REP	Rotating Electrode Process
RF	Radio Frequency

RGB	Red-Green-Blue
RLS	Recursive Least Square
RMSE	Root Mean Square Error
RNN	Recurrent Neural Networks
ROS	Reactive Oxygen Species
RTE	Radiation Transfer Equation
SAW	Surface Acoustic Wave
SD	Signal Dynamics
SDAS	Secondary Dendritic Arm Spacing
SE	Secondary Electrons
SIMP	Solid Isotropic Material with Penalization
SINH	Sine Hyperbolic Function
SL	Sheet Lamination
SLD	Super-Luminescent Diode
SLD-OCT	Super-Luminescent Diode—Optical Coherence Tomography
SLM	Selective Laser Melting
SLP	Sequential Linear Programming
SLR	Single-Lens Reflex
SLS	Selective Laser Sintering
SN	Small Negative
SOM	Self-Organizing Map
SP	Small Positive
SQP	Sequential Quadratic Programming
SRAS	Spatially Resolved Acoustic Spectroscopy
STF	Short-Term Fluctuations
STL	Standard Tessellation Language or StereoLithography
STP	Standard for the Product Data
ST-PCA	Spatially Weighted Principal Component Analysis
SVD	Singular Value Decomposition
SVM	Support Vector Machine
TCP	Topological Close-Packed
TEM	Transverse Electromagnetic Modes
TGM	Temperature Gradient Mechanism
Ti	Titanium
TiC	Titanium Carbide
Ti-HA	Titanium-Hydroxyapatite
TMCs	Titanium-Matrix Composites
TN	True Negative
TP	True Positive
TPMS	Triply Periodic Minimal Surface
TRL	Technology Readiness Level
TTT	Transformation Time Temperature
VC	Vanadium Carbides
VED	Volumetric Energy Density
VoF	Volume-of-Fluid
VTM	Virtual Temperature Method
WF	Wire-Fed
WF-EDED	Wire-Fed Electron Beam Directed Energy Deposition
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

YAG Yttrium Aluminum Garnet
YLF Yttrium Lithium Fluoride
YVO4 Yttrium Orthovanadate

Nomenclature

Unless otherwise stated in the text, these symbols have the following meanings

a	Characteristic length
a	Energy bilinear function for internal energy (Chapter 10)
A	Spot area – heat source interaction area
A	Filament or nozzle cross-section area (Chapter 7)
A_{at}	Attenuated area
A_c	Cross-section area
A_{jet}^{liq}	Intersection of melt pool area on substrate and powder stream
A_{jet}	Cross-section of powder stream on substrate
A_G	Property of filament material
A_{ij}, B_{ij}	Einstein coefficients
A_S	Surface area
b	Melt pool depth
b	Bias (Chapter 11)
B	Size of gap (Chapter 7)
B	Magnetic field
$\boldsymbol{B}$	Differential shape function matrix (Chapter 10)
c	Speed of light
c_p	Heat capacity
cyl	Function based on Bessel functions
c_s	Speed of sound in the fluid
C	Duty cycle
C	Compliance (Chapter 10)
Ca	Capillary number
C_s	Solid composition
C_L	Liquid composition
C_0	Nominal alloy composition or solute concentration
d	Spot size
d	Euclidean distance (Chapter 11)
d_0	Droplet diameter
$d_{3,2}$	Surface mean particle diameter
d_{con}	Semispherical droplet
D	Laser beam diameter
$\boldsymbol{D}$	Material matrix
D_f	Diffusion constant
D_{ijmn}	Tensor of elastic coefficients
D_L	Solute diffusion coefficient

$D_Ø$	Diffusion coefficient
e	When subscript or superscript, signifies a variable in its elemental form
e_i	Vector pointing
E	Laser beam energy
E	Electric field (Chapter 5)
$\boldsymbol{E}$	Young's modulus matrix (Chapter 10)
E_a	Energy of activation
E_b	E-beam energy
E_i	Input laser energy
E_{kin}	Kinetic energy
E_r	Reflected energy
E_t	Transmitted energy
E_i	Energy levels (Chapter 3)
$E_{specific}$	The energy enters the substrate from the surface in DED
f	Frequency
f	Volume fraction (Chapter 10)
f_s	Fraction of solid
f_L	Fraction of liquid
$f(R)$	Function of surface roughness
$f_i(x, t)$	Density of particles moving in the e_i direction
$f_i^{eq}(x,t)$	Equilibrium distribution
F	Force
F_0	Fourier number
$\mathcal{F}_0$	Zero-order Bessel function of its first kind
$\mathcal{F}_1$	The first-order Bessel function of the first kind
F^{Cap}	Capillary force
F_{st}	Surface tension force
F_{th}	Thermal stress load
F^{Wet}	Wetting force
g	Gravity
g_i	Effect of external forces
G	Temperature gradient
G_S	Gibbs free energy for solid
G_L	Gibbs free energy for liquid
G_z	Graetz number
ΔG	Total Gibbs free energy change
ΔG^*	Critical free energy change
ΔG_V	Free energy change per unit volume
h	Plank's constant (Chapter 3)
h	Height of a hexahedral element (Chapter 10)
h_c	Heat convection coefficient
h_i	Convective heat loss (cooling) coefficients
h_a	Average heat transfer coefficient of convection
h_w	Distance between the nozzle and surface
h_r	Radiative heat transfer coefficient

h_{min}	Minimum radius of the liquid column
H	Barrel length or height of track
H^*	Height of the melt polymer
ΔH	Enthalpy difference
HDR	Heating depth ratio
I	Intensity: energy per area
I	Current in electron beam (Chapter 5)
$I(x)$	Indicator function (Chapter 11)
I_0	Intensity scale factor or initial intensity
I_b	Beam current in the electron-beam process
J	Free electron current
k	Propagation factor
k	Equilibrium distribution coefficient (Chapter 8)
k	Solute partition coefficient (Chapter 9)
K	Thermal conductivity
$\boldsymbol{K}$	Global stiffness matrix (Chapter 10)
$\boldsymbol{K_c}$	Conductivity matrix (Chapter 10)
$\boldsymbol{K_h}$	Connective matrix (Chapter 10)
K^*	Modified thermal conductivity
K_0	Bessel function of the second kind and zero order
l	Layer thickness
l	Load linear function for external work (Chapter 10)
$\boldsymbol{L}$	Transformation matrix
L	Link intensity
L_c	Characteristic length based on domain size
L_f	Latent heat of fusion
L_l^p	Laguerre polynomial of order p and index l
m	Atomic mass
m_b	Mass of the ball (Chapter 9)
m_b	Deposited binder (Chapter 6)
m_p	Particle mass
m_p	Mass of the bound powder (Chapter 6)
m_f	Fluid mass
$\dot{m}$	Mass flow rate
M^2	Beam quality factor
Ma	Marangoni number
n	Reflection's index
N	Matrix of shape function for mesh element
N_i	Number of atoms or electrons per unit volume in the energy levels
N_L	Amount of atoms per unit volume of liquid
N_{lx}	Neumann function
N_S	Amount of atoms per unit volume of solid
Nu	Nusselt number
N_{th}	Shape vector for thermal expansion
Oh	Ohnesorge number

p	Constant characteristic of the material (Chapter 4)
p	Pressure
p	Penalty value (Chapter 10)
p_c	Capillary force
P_f	Packing fraction
P	Power
P_{at}	Attenuated laser power by particles
P_{el}	Power of electrical motor in FDM system
P_l	Net/average laser power
P_{peak}	Peak power per pulse
P_{on}	On the state of the laser power
P_{off}	Off state of the laser power
P_{tot}	Total delivered beam power
P_e	Peclet number
Pr	Prandtl number
PR	Packing density of the powder
PW	Pulsed wave laser
$P(\infty)$	Value of the extrudate property after an infinite healing time
q	Heat flux
Q	Power generated per unit volume (in all chapters except Chapter 3)
Q	Beam propagation factor (Chapter 3)
Q_c	Total energy absorbed by the substrate
Q_{ext}	Extinct coefficient
Q_l	Laser energy
Q_{rs}	Reflected energy from the substrate
Q_L	Latent energy of fusion
Q_v	Volumetric flow rate
r	Radius of nucleus (Chapter 8)
r^*	Critical nucleus radius
r_b	Ball mill radius
r_f	Filament radius
r_{0l}	Beam radius of the waist
r_{jet}	Radius of powder spray jet
r_l	Beam spot radius on the substrate
r_s	Powder stream diameter
r_p	Powder particle radius
R	Reflectivity
R	Solidification rate where it is referred to
R_c	Clad surface curvature
R_{cur}	Radius of curvature
Re	Reynolds number
Re^*	Property-based Reynolds number
R_h	Heat load by convection
$R_h(t)$	Intrinsic healing function
R_L	Local growth rate

R_N	Nominal growth rate
R_r	Radius of the actuating motor
R_{pore}	Effective pore diameter in the bed
R_q	Heat load by surface conduction
R_Q	Heat load by volume conduction
s	Hatch spacing
s_0	Specific surface area
S	Binder saturation
S_{ij}	Lateral distance between neuron *i* and *j* (Chapter 11)
S_{max}	Spreading ratio
S_{meas}	Amount of signal (Chapter 11)
$S_{Ø}$	Source term corresponding to Ø
$S\ (\phi)$	Shape factor
SS	Scan speed
S	Strain rate deformation tensor
ΔS	Expansion of surface area
t	Time and/or laser interaction time
t^*	Dimensionless time
$t_c = t_\mu$	Viscous time
t_{CDA}	Corresponding penetration time
t_f	Solidification time
t_I	Inertial-capillary time
t_V	Viscous-capillary time
T	Temperature
T_α	Reference temperature
T_{ave}	Average temperature
T_{in}	Filament temperature
T_g	Glass transition temperature
T_{out}	Outlet temperature
$T_{\dot{m}}$	Temperature of the liquefier wall
T_d	Drying time
T_e	Equilibrium temperature
T_l	Liquidus temperature
T_0	Ambient temperature
T_m	Materials melting point
T_p	Maximum temperature
ΔT	Undercooling temperature
ΔT_{tot}	Total undercooling temperature
ΔT_C	Undercooling temperature: solute diffusion
ΔT_T	Undercooling temperature: thermal diffusion
ΔT_K	Undercooling temperature: attachment kinetics
ΔT_R	Undercooling temperature: solid–liquid boundary curvature
TEM_{pl}	Gaussian–Laguerre transverse electromagnetic modes
U	Beam velocity
$\boldsymbol{U}$	Travel velocity vector

$\boldsymbol{U}$	Global displacement vector (Chapter 10)
$\boldsymbol{U_p}$	Particle velocity vector
U_s	Rate of solidification
v	Scanning speed
v_c	Collision velocity
υ_j	Jet velocity
v_p	Velocity of the particle
v_{print}	Velocity of the print head
V	Volume of melt pool
$\boldsymbol{V}$	Design volume (Chapter 10)
V_a	Acceleration voltage
V_S	Volume of nucleus
VED	The energy enters the substrate from the surface in LPBF
w	Track or melt pool width
w	Neuron weight (Chapter 11)
w_i	Weight factor
W	Laser pulse width
We	Weber number
X_{s+c}	Weight percent of element X in the total surface of the clad region
X_c	Weight percent of element X in the powder alloy
X_s	Weight percent of element X in the substrate
y	Dendrite arm spacing (Chapter 8)
z	Distance from the surface
z_0	Waist location with respect to an arbitrary coordinate along the propagation axis
Z	Printability of a liquid
Z_h	Heat penetration depth

Greek Symbols

α	Thermal diffusivity
α_t	Coefficient of thermal expansion
β	Absorption factor
β	Absorption factor
β_p	Powder particles' absorbed coefficient
β_w	Substrate laser power absorptivity
γ	Surface tension
γ	Net electron beam energy (Chapter 5)
γ_E	Specific surface energy
γ_{SL}	Solid–liquid interfacial free energy
γ_{SV}	Solid–vapor interfacial energy
γ_{LV}	Liquid–vapor interfacial energy
$\dot{\gamma}$	Shear rate
$\mathit{\Gamma}$	Torque of electrical motors in FDM
Γ	Surface function (Chapter 10)
δ	Solid/liquid interface thickness
$\mathrm{\delta}$	Dirac delta function (Chapter 6)

$\boldsymbol{\varepsilon}$	Total strain
ε_c	Cooling rate
ε_t	Emissivity
ε^M	Mechanical strains
ε^T	Thermal strains
ε_p	Equivalent plastic stress
ε_0	Vacuum permittivity
$\boldsymbol{\varepsilon_m}$	Mechanical strain
$\boldsymbol{\varepsilon_{th}}$	Thermal strain
Σ	Covariance matrix
η	Dynamic viscosity
η	Powder catchment efficiency (wherever it refers to throughout chapters)
η	Numerical damping coefficient for OCM (Chapter 10)
η	Learning rate (Chapter 11)
η_e	Absorption efficiency for electron beam
η_d	Dynamic viscosity
η_p	Powder catchment efficiency
θ	Representing different angles based on figures
θ	Wetting angle (Chapter 2)
θ	Far-field divergence angle (Chapter 3)
θ	Dimensionless temperature in numerical models (Chapter 7)
θ_{jet}	Angle between powder jet and substrate
θ_d	Dynamic wetting angle
θ_{eq}	Steady-state angle
Θ	Dimensionless temp in analytical models
λ	Wavelength
λ	Lagrange multiplier (Chapter 10)
λ_n	Roots of zero-order Bessel function of its first kind
μ	Viscosity
μ	Membership function (Chapter 11)
υ	Frequency (Chapter 3)
υ	Kinematic viscosity
ρ	Density
ρ_b	Density of binder
ρ_{pb}	Powder bed density
ρ_c	Density of melted powder alloy
ρ_s	Density of substrate material
ρ_s	Packing density of the pores (Chapter 6)
σ	Stefan–Boltzmann constant
σ	Covariance (Chapter 11)
σ_c	Charge density
σ_{ij}	Elastic stress
τ	Thermal time constant
τ_c	Dimensionless capillary time
ϕ	Different label for angles as indicated in the associated figures