

# Table of Contents

[Cover](#)

[Title Page](#)

[Copyright Page](#)

[Dedication Page](#)

[Preface](#)

[Abbreviations](#)

[Nomenclature](#)

[Greek Symbols](#)

[1 Additive Manufacturing Process Classification, Applications, Trends, Opportunities, and Challenges](#)

[1.1 Additive Manufacturing: A Long-Term Game Changer](#)

[1.2 AM Standard Definition and Classification](#)

[1.3 Why Metal Additive Manufacturing?](#)

[1.4 Market Size: Current and Future Estimation](#)

[1.5 Applications of Metal AM](#)

[1.6 Economic/Environmental Benefits and Societal Impact](#)

[1.7 AM Trends, Challenges, and Opportunities](#)

[1.8 Looking Ahead](#)

[References](#)

[2 Basics of Metal Additive Manufacturing](#)

[2.1 Introduction](#)

[2.2 Main Metal Additive Manufacturing Processes](#)

[2.3 Main Process Parameters for Metal DED, PBF, and BJ](#)

## [2.4 Materials](#)

## [References](#)

# [3 Main Sub-Systems for Metal AM Machines](#)

## [3.1 Introduction](#)

## [3.2 System Setup of AM Machines](#)

## [3.3 Laser Basics: Important Parameters Needed to be Known for AM](#)

## [3.4 Electron Beam Basics](#)

## [3.5 Powder Feeders and Delivery Nozzles Technology](#)

## [3.6 CAD File Formats](#)

## [3.7 Summary](#)

## [References](#)

# [4 Directed Energy Deposition \(DED\)](#)

## [4.1 Introduction](#)

## [4.2 Laser Material Interaction and the Associated Significant Parameters to Laser AM](#)

## [4.3 E-beam Material Interaction](#)

## [4.4 Power Density and Interaction Time for Various Heat Source-based Material Processing](#)

## [4.5 Physical Phenomena and Governing Equations During DED<sup>1</sup>](#)

## [4.6 Modeling of DED](#)

## [4.7 Case Studies on Common Modeling Platforms for DED](#)

## [4.8 Summary](#)

## [References](#)

# [5 Powder Bed Fusion Processes](#)

## [5.1 Introduction and Notes to Readers](#)

[5.2 Physics of Laser Powder bed Fusion \(LPBF\)](#)

[5.3 Physics and Modeling of Electron Beam Additive Manufacturing](#)

[References](#)

[6 Binder Jetting and Material Jetting](#)

[6.1 Introduction](#)

[6.2 Physics and Governing Equations](#)

[6.3 Numerical Modeling](#)

[6.4 Summary](#)

[References](#)

[7 Material Extrusion](#)

[7.1 Introduction](#)

[7.2 Analytical Modeling of ME](#)

[7.3 Numerical Modeling of ME](#)

[7.4 Summary](#)

[References](#)

[8 Material Design and Considerations for Metal Additive Manufacturing](#)

[8.1 Historical Background on Materials](#)

[8.2 Materials Science: Structure-Property Relationship](#)

[8.3 Manufacturing of Metallic Materials](#)

[8.4 Solidification of Metals: Equilibrium](#)

[8.5 Solidification in Additive Manufacturing: Non-Equilibrium](#)

[8.6 Equilibrium Solidification: Theory and Mechanism](#)

[8.7 Non-Equilibrium Solidification: Theory and Mechanism](#)

[8.8 Solute Redistribution and Microsegregation](#)

[8.9 Constitutional Supercooling](#)  
[8.10 Nucleation and Growth Kinetics](#)  
[8.11 Solidification Microstructure in Pure Metals and Alloys](#)  
[8.12 Directional Solidification in AM](#)  
[8.13 Factors Affecting Solidification in AM](#)  
[8.14 Solidification Defects](#)  
[8.15 Post Solidification Phase Transformation](#)  
[8.16 Phases after Post-Process Heat Treatment](#)  
[8.17 Mechanical Properties](#)  
[8.18 Summary](#)  
[References](#)

## [9 Additive Manufacturing of Metal Matrix Composites](#)

[9.1 Introduction](#)  
[9.2 Conventional Manufacturing Techniques for Metal Matrix Composites \(MMCs\)](#)  
[9.3 Additive Manufacturing of Metal Matrix Composites \(MMCs\)](#)  
[9.4 AM Challenges and Opportunities](#)  
[9.5 Preparation of Composite Materials: Mechanical Mixing](#)  
[9.6 Different Categories of MMCs](#)  
[9.7 Additive Manufacturing of Ferrous Matrix Composites](#)  
[9.8 Additive Manufacturing of Titanium-Matrix Composites \(TMCs\)](#)  
[9.9 Additive Manufacturing of Aluminum Matrix Composites](#)  
[9.10 Additive Manufacturing of Nickel Matrix Composites](#)

[9.11 Factors Affecting Composite Property](#)

[9.12 Summary](#)

[References](#)

[10 Design for Metal Additive Manufacturing](#)

[10.1 Design Frameworks for Additive Manufacturing](#)

[10.2 Design Rules and Guidelines](#)

[10.3 Topology Optimization for Additive Manufacturing](#)

[10.4 Lattice Structure Design](#)

[10.5 Design for Support Structures](#)

[10.6 Design Case Studies](#)

[10.7 Summary](#)

[References](#)

[11 Monitoring and Quality Assurance for Metal Additive Manufacturing](#)

[11.1 Why are Closed-Loop and Quality Assurance Platforms Essential?\[1\]<sup>1</sup>](#)

[11.2 In-Situ Sensing Devices and Setups](#)

[11.3 Commercially Available Sensors](#)

[11.4 Signal/Data Conditioning, Methodologies, and Classic Controllers for Monitoring, Control, and Quality Assurance in Metal AM Processes](#)

[11.5 Machine Learning for Data Analytics and Quality Assurance in Metal AM](#)

[11.6 Case Study](#)

[11.7 Summary](#)

[References](#)

[12 Safety](#)

[12.1 Introduction](#)

[12.2 Overview of Hazards](#)

[12.3 AM Process Hazards](#)

[12.4 Laser Safety in Additive Manufacturing<sup>1</sup>](#)

[12.5 Electron Beam Safety](#)

[12.6 Powder Hazards](#)

[12.7 Human Health Hazards](#)

[12.8 Comprehensive Steps to AM Safety Management](#)

[12.9 Summary](#)

[References](#)

[Index](#)

[End User License Agreement](#)

## List of Tables

### Chapter 2

[Table 2.1 Configurations of major commercially available PBF systems.](#)

[Table 2.2 The market cost of wire and AM grade powder per pound for some of ...](#)

[Table 2.3 Configurations of commercially available DED systems.](#)

[Table 2.4 Configurations of commercially available BJ systems.](#)

[Table 2.5 Influence of increasing process parameters on dimensions of a sing...](#)

### Chapter 3

[Table 3.1 Comparison between AM processes adapted from \[16\] with several cha...](#)

[Table 3.2 Comparisons of some representative AM processes.](#)

## Chapter 4

[Table 4.1 Optical properties and Brewster angle of several materials for 106...](#)

[Table 4.2 Reflectivity of different surface roughness for a 10.6- \$\mu\$ m waveleng...](#)

## Chapter 5

[Table 5.1 Material input parameters for LPBF \[2, 3\].](#)

[Table 5.2 Equations used for powder particles shape characterization \[18\].](#)

[Table 5.3 Parameters for the single-layer multiple-track scanning.](#)

[Table 5.4 Melt pool depths in the multi-track scanning.](#)

## Chapter 8

[Table 8.1 Phase formation during solidification of different types of AM ste...](#)

[Table 8.2 Phase formation during solidification of different types of AM Al ...](#)

[Table 8.3 Chemical composition of different superalloys.](#)

[Table 8.4 Post solidification phases of In625.](#)

[Table 8.5 Post solidification phases of IN718.](#)

[Table 8.6 Different types of Stellite.](#)

[Table 8.7 Post solidification phases of Stellite.](#)

[Table 8.8 Post solidification phases of Ti alloys.](#)

[Table 8.9 The estimated cooling rates necessary to obtain various morphologi...](#)

## Chapter 9

[Table 9.1 Summary of microstructures formed in TMCs.](#)

[Table 9.2 Mechanical and wear property of CP-Ti and different kinds of TMCs ...](#)

## Chapter 10

[Table 10.1 Metal additive technologies compared with key design consideratio...](#)

[Table 10.2 Topology optimization of point loaded structures.](#)

[Table 10.3 Objectives and constraints for topology optimization of arbor pre...](#)

[Table 10.4 Arbor press components and mass composition.](#)

[Table 10.5 Design space and optimized result of arbor press components.](#)

[Table 10.6 Design iterations for framework.](#)

## Chapter 11

[Table 11.1 Co-axial mounted based sensors used in LPBF and LDED.](#)

[Table 11.2 Off-axial mounted based sensors used in LPBF and LDED.](#)

[Table 11.3 Some commercial sensors mounted on the LPBF machines.](#)

[Table 11.4 Some commercial sensors mounted on LDED machines.](#)



[Table 11.5 Calibration of RGB values with temperature. For colorful spectrum...](#)

[Table 11.6 Machine learning methods used in LPBF and LDED.](#)

[Table 11.7 Performance of different SOM dimensions based on the SOEDNN.](#)

[Table 11.8 Types and print parameters in print 1.](#)

[Table 11.9 Types and print parameters in print 2.](#)

[Table 11.10 Applying the detection algorithms on the five consecutive layers...](#)

[Table 11.11 The range of  \$p\$ -value from ANOVA single-factor analysis of the var...](#)

[Table 11.12 The percentage of identification for each size of the defect and...](#)

[Table 11.13 Confusion matrix to compare the prediction of the algorithm \(AL\)...](#)

[Table 11.14 Evaluation metrics of AL algorithm based on the CT scan result f...](#)

[Table 11.15 Evaluation metrics of AL algorithm based on the CT scan result f...](#)

## Chapter 12

[Table 12.1 Related potential hazards by metal AM process category \[3\].](#)

[Table 12.2 Different  \$K\_{st}\$  values for different materials and their severity.](#)

[Table 12.3 National Fire Protection Association \(NFPA\) standards \[13\].](#)

## List of Illustrations

## Chapter 1

[Figure 1.1 Global public interest trends for “3D Printing”.](#)

[Figure 1.2 AM chain, enabling physical parts from digital design.](#)

[Figure 1.3 Complex parts made by AM. The spherical nest has three spheres in...](#)

[Figure 1.4 Lightweight structure made by AM. In this typical bracket, the we...](#)

[Figure 1.5 Consolidation of around 300 parts to one part printed by AM.](#)

[Figure 1.6 Functionally graded materials \(FGMs\); \(a\) Laser DED with multiple...](#)

[Figure 1.7 A fiber optic embedded in a metallic cutting part using a combine...](#)

[Figure 1.8 A mold insert with \(a\) conformal cooling channels, \(b\) conformal ...](#)

[Figure 1.9 LDED used to rebuild turbine blades.](#)

[Figure 1.10 Total AM market size by segment that includes all technologies \(...\)](#)

[Figure 1.11 Metal AM market size in AMPower Report.](#)

[Figure 1.12 Timeline for adopted, emerging, and future applications of AM.](#)

[Figure 1.13 Most important metal AM processes versus part size, complexity, ...](#)

[Figure 1.14 \(a\) Dental crowns printed by LPBF \(b\) joint implants printed ...](#)

[Figure 1.15 LPBF-made combustion chamber \(left\) and the engine in finished c...](#)

[Figure 1.16 Small-size, lightweight, one-piece, AM-made antenna.](#)

[Figure 1.17 Hydraulic parts made for the oil and gas industry.](#)

[Figure 1.18 \(a\) Ford's custom anti-theft wheel lock being printed in EOS PBF...](#)

[Figure 1.19 MX3D smart bridge \(a\) main structure \(b\) side wall.](#)

[Figure 1.20 \(a\) Three different geometries made of Ti-6Al-4V by different pr...](#)

## Chapter 2

[Figure 2.1 Schematic of \(a\) LPBF and \(b\) EB-PBF.](#)

[Figure 2.2 A view of melt pool and ejected spatters in LPBF.](#)

[Figure 2.3 Samples of metal parts made via PBF for \(a\) aerospace, \(b\) toolin...](#)

[Figure 2.4 The CT scan results of \(i\) cylindrical, \(ii\) triangular prism, an...](#)

[Figure 2.5 Schematics of \(a\) powder-fed laser DED with lateral nozzle\(b\)...](#)

[Figure 2.6 Applications of DED: \(a\) Near-net-shape production.\(b\) Freefo...](#)

[Figure 2.7 A sample of repaired rotating part using Optomec® LENS DED system...](#)

[Figure 2.8 A schematic of binder jetting technology.](#)

[Figure 2.9 ExOne binder jetting technology in Action.](#)

[Figure 2.10 HP multi-jet fusion technique steps.](#)

[Figure 2.11 Sample part made using BJ technology.](#)

[Figure 2.12 Comparison of traditional binder jetting and Desktop Metal's bin...](#)

[Figure 2.13 Schematic of material extrusion system.](#)

[Figure 2.14 A sample metal filament from Desktop Metal. In contrast to polym...](#)

[Figure 2.15 Visual prototypes made using \(a\) 17-4 PH stainless steel on Mark...](#)

[Figure 2.16 Schematic of material jetting technology.](#)

[Figure 2.17 XJET's NanoParticle Jetting technique is one of the emerging met...](#)

[Figure 2.18 Sample parts made using XJET system.](#)

[Figure 2.19 Ultrasonic consolidation mechanism.](#)

[Figure 2.20 FGM parts made using Fabrisonic's ultrasonic consolidation syste...](#)

[Figure 2.21 Process design parameters for LDED, LPBF, and BJ techniques.](#)

[Figure 2.22 Melt pool and clad/track bead geometrical parameters.](#)

[Figure 2.23 Relative density vs. energy for various ferrous alloys \(a\) relat...](#)

[Figure 2.24 Normalized density vs. specific energy techniques.](#)

[Figure 2.25 Common scanning strategies.](#)

[Figure 2.26 \(a\) Keyhole porosity and its formation mechanism.\(b\) Lack of...](#)

[Figure 2.27 The combined effect of scanning velocity and beam power on the d...](#)

[Figure 2.28 The relationship between melt-pool geometry and hatching distanc...](#)

[Figure 2.29 Porosity of LPBF-made parts from AlSi10Mg as a function of hatch...](#)

[Figure 2.30 Classification of powder particle properties.](#)

[Figure 2.31 The relationship between particle and flow properties and flowab...](#)

[Figure 2.32 Different wire-feeding orientations.](#)

[Figure 2.33 Illustration of the staircase effect.](#)

[Figure 2.34 The maximum layer thickness as a measure of the overlap height o...](#)

[Figure 2.35 Cross section of a part as the print layer: contour/skin and cor...](#)

[Figure 2.36 \(a, b\) Illustration of up-skin vs down-skin in PBF process.\(...](#)

[Figure 2.37 The concept of supports structures, three different support shap...](#)

[Figure 2.38 Printability of the fluids based on dimensionless Reynolds and W...](#)

[Figure 2.39 The effects of \(a\) undersaturation and \(b\) oversaturation on BJ-...](#)

[Figure 2.40 H13 tool steel powder agglomeration as a result of oversaturatio...](#)

## Chapter 3

[Figure 3.1 Laser powder bed fusion system \(LPBF\).](#)

[Figure 3.2 Laser Powder-Fed \(LPF\) system.](#)

[Figure 3.3 Schematic of a binder jetting system setup.](#)

[Figure 3.4 Illustration of the absorption, spontaneous emission, and stimula...](#)

[Figure 3.5 Two-level system scheme.](#)

[Figure 3.6 A three-level system scheme.](#)

[Figure 3.7 Scheme of a four-level system.](#)

[Figure 3.8 The main components of a laser are shown. The active medium or ga...](#)

[Figure 3.9 Solid-state Laser scheme.](#)

[Figure 3.10 Energy-level diagram for Nd<sup>3+</sup> doped in YAG.](#)

[Figure 3.11 \(a\) Longitudinally excited and \(b\) transversely excited CO<sub>2</sub> lase...](#)

[Figure 3.12 Laser transitions between vibrational levels in CO<sub>2</sub>.](#)

[Figure 3.13 Liquid dye laser schematic.](#)

[Figure 3.14 Diode laser scheme.](#)

[Figure 3.15 Scheme of a typical fiber laser.](#)

[Figure 3.16 Schematic of fiber lasers that include FBGs and beam coupler](#)

[Figure 3.17 Energy-level diagram of the erbium-doped fiber.](#)

[Figure 3.18 Laser employed in laser-based AM processes \(i.e. laser powder be...](#)

[Figure 3.19 Mode patterns for different TEMs.](#)

[Figure 3.20 Laser beam profile.](#)

[Figure 3.21 Schematic of a typical EBM apparatus.](#)

[Figure 3.22 Electron beam formation schematic.](#)

[Figure 3.23 Gun electrode types: \(a\) Tungsten \(W\) filament, \(b\) Lanthanum He...](#)

[Figure 3.24 Electromagnetic Lens.](#)

[Figure 3.25 Scheme of a mechanical wheel powder feeder.](#)

[Figure 3.26 Schematic of gravity-based powder feeders with a rotating wheel ...](#)

[Figure 3.27 Schematic of gravity-based powder feeders with a metering wheel....](#)

[Figure 3.28 Schematic of gravity-based powder feeders with a lobe gear.](#)

[Figure 3.29 Schematic of a fluidized bed powder feeder.](#)

[Figure 3.30 Schematic of a vibratory-based powder feeder.](#)

[Figure 3.31 Schematic of a typical lateral nozzle.](#)

[Figure 3.32 Powder feed profile characteristics.](#)

[Figure 3.33 Schematic of a typical coaxial nozzle.](#)

[Figure 3.34 Powder stream at the nozzle exit to a co-axial nozzle.](#)

[Figure 3.35 Illustration of a LPBF process system setup.](#)

[Figure 3.36 Schematic of a lateral wire-feed system equipped with EBM.](#)

[Figure 3.37 Schematic of a coaxial wire-feed system.](#)

[Figure 3.38 Schematic of a galvo scanner.](#)

[Figure 3.39 Schematics of \(a\) piezo and \(b\) thermal inkjet print heads.](#)

[Figure 3.40 Typical STL file.](#)

## Chapter 4

[Figure 4.1 Interaction of a moving heat source and a substrate and the assoc...](#)

[Figure 4.2 Schematic of phases formed in a mild steel substrate while being ...](#)

[Figure 4.3 Sinusoidal electromagnetic laser beam: emitted beam, reflected be...](#)

[Figure 4.4 Graphical concept of the thermal time constant.](#)

[Figure 4.5 Laser pulse shaping, including pulse width  \$W\$ , pulse energy  \$E\$ , and...](#)

[Figure 4.6 A typical modulated/pulsed laser beam with rising time, falling t...](#)

[Figure 4.7 Dependencies of reflectivity to wavelengths, \(a\) from 200 to 1000...](#)

[Figure 4.8 Temperature dependencies of reflectivity for Al, Cu, and steel at...](#)

[Figure 4.9 Dependencies of reflectivity to the angle of incidence for s-ray ...](#)

[Figure 4.10 E-beam interaction with a substrate and the associated signals g...](#)

[Figure 4.11 Penetration depth versus absorption coefficient for accelerated ...](#)

[Figure 4.12 Power density and interaction time for various heat source-based...](#)

[Figure 4.13 Schematic of physical domains of DED.](#)



[Figure 4.14 Track cross section created by DED, \(a\). high dilution, well wett...](#)

[Figure 4.15 Dynamic and equilibrium wetting angles.](#)

[Figure 4.16 A schematic of the process zone during LDED powder-fed. Melting ...](#)

[Figure 4.17 Geometry and boundary conditions for a typical coaxial nozzle ex...](#)

[Figure 4.18 Schematic of 3D heat flow during DED used for the development of...](#)

[Figure 4.19 Balance of energy in PF-LDED.](#)

[Figure 4.20 Lumped cross section of single track deposited in LDED.](#)

[Figure 4.21 Attenuated laser volume in PF-LDED.](#)

[Figure 4.22 Lumped temperature distribution at  \$y = 0\$  for parameters listed i...](#)

[Figure 4.23 Schematic diagram for laser powder-fed laser-directed deposition...](#)

[Figure 4.24 Inconel 625 powder stream grayscale intensity distribution measu...](#)

[Figure 4.25 Schematic diagram for melt pool geometry and deposited track \[27...](#)

[Figure 4.26 Schematic diagram of the solidification front in the longitudina...](#)

[Figure 4.27 Laser beam intensity distribution on the substrate surface: \(a\)...](#)

[Figure 4.28 Melt pool temperature distribution on Inconel 625 substrate surf...](#)

[Figure 4.29 Real-time melt pool top surface peak temperature of SS 316L depo...](#)

[Figure 4.30 Melt pool peak temperature map for SS 316L single-track depositi...](#)

[Figure 4.31 Real-time local thermal profiles at different clad height locati...](#)

[Figure 4.32 Effect of  \$G\$  and  \$R\$  on the mode and scale of solidification micros...](#)

[Figure 4.33 Predicted in situ solidification characteristics at different me...](#)

[Figure 4.34 Schematic of the laser beam, powder stream and substrate interac...](#)

[Figure 4.35 Sequence of calculation in the proposed numerical model \[37\]...](#)

[Figure 4.36 Maximum temperatures for each layer, when  \$\dot{m} = 2\$  g/min,  \$U = 1.5\$  m...](#)

[Figure 4.37 Temperature distribution for the second layer deposition at  \$t = \dots\$](#)

[Figure 4.38 Energy transformations within the deposition area of a substrate...](#)

[Figure 4.39 Deposition patterns in wire-fed EBAM.](#)

[Figure 4.40 Proposed Hammerstein-Wiener nonlinear structure](#)

[Figure 4.41 Experimental data: \(a\) multistep process speed and \(b\) clad/depo...](#)

[Figure 4.42 Verification of Hammerstein-Wiener dynamic model using unseen da...](#)

## Chapter 5

[Figure 5.1 Schematic of LPBF, showing physical phenomena surrounding the mel...](#)

[Figure 5.2 Heat source models schematics: \(a\) cylindrical shape; \(b\) semi-sp...](#)

[Figure 5.3 Powder-laser interaction mechanisms.](#)

[Figure 5.4 Thermophysical properties of bulk and powder material: \(a\) therma...](#)

[Figure 5.5 Schematic of \(a\) keyhole mode and \(b\) conduction mode. Top figure...](#)

[Figure 5.6 Temperature gradient mechanism inducing residual stress.](#)

[Figure 5.7 The laser scanning path used for the case study.](#)

[Figure 5.8 Geometry and mesh used in the finite element simulation of the ca...](#)

[Figure 5.9 Ripples of a single track: \(a\) experimental results and \(b\) numer...](#)

[Figure 5.10 Experimental surface of the multiple-track scanning: \(a\) microsc...](#)

[Figure 5.11 Melt pool cross section of a single track from \(a\) experiment \(b...](#)

[Figure 5.12 Multi-track melt pool cross sections: \(a\) experiment and \(b\) sim...](#)

[Figure 5.13 Schematic of the theoretical model of the LPF process.](#)

[Figure 5.14 Electron acceleration between anode and cathode and electric pot...](#)

[Figure 5.15 Binary head-on collision of particles in a hexagonal grid model ...](#)

[Figure 5.16 Three-dimensional projection of a face-centered hypercubic latti...](#)

[Figure 5.17 Phases assigned to different cells in the LB method. The specifi...](#)

[Figure 5.18 Exponential \(60 kV\) and constant \(120 kV\) absorption profiles....](#)

[Figure 5.19 Melt pool evolution during EB-PBF processing using the LB method...](#)

[Figure 5.20 \(a\) Rain model schematic. \(b\) Generated powder bed. \(c\) Relative...](#)

[Figure 5.21 Gaussian EB model using the constant absorption profile.](#)

[Figure 5.22 \(a\) Micro-scale simulation temperature distribution for a scan l...](#)

[Figure 5.23 Strain evolution of a part during the build process.](#)

[Figure 5.24 Comparison between the FEM model and produced parts. It uses the...](#)

## Chapter 6

[Figure 6.1 Schematic of \(a\) continuous inkjet printing showing the working m...](#)

[Figure 6.2 The droplet formation and flight in inkjet printing. The tail of ...](#)

[Figure 6.3 \(a\) The thinning of the jet on the onset of droplet formation in ...](#)

[Figure 6.4 The pinch-off of liquid column as time passes for a liquid with r...](#)

[Figure 6.5 Schematic of surface wettability for a droplet of water as a func...](#)

[Figure 6.6 Droplet impact regimes on dry surfaces.](#)

[Figure 6.7 Droplet cross section changes as a function of time from impact t...](#)

[Figure 6.8 Infiltration of the droplet into \(a\) dry and \(b\) - \(c\) pre-wetted...](#)

[Figure 6.9 The wetted region imaged using micro-CT for one droplet dispensed...](#)

[Figure 6.10 The creation of crater geometry: \(a\) droplet approaching the sur...](#)

[Figure 6.11 Schematic of liquid bridge between two identical spherical parti...](#)

[Figure 6.12 The penetration of a droplet with the impact velocity of 5 m/s i...](#)

[Figure 6.13 Droplet formation modeling using level-set method showing the ef...](#)

[Figure 6.14 \(a\) Sample D2Q9 LBM.\(b\) Lattice vectors in a D2Q9 cell.](#)

[Figure 6.15 Streaming step in LBM.](#)

[Figure 6.16 Collision step in LBM.](#)

[Figure 6.17 \(a\) 2D view of droplet spreading on a smooth surface from initia...](#)

## Chapter 7

[Figure 7.1 Components of a typical printhead in a ME system.](#)

[Figure 7.2 HF composite filament at different ME process stages: Metal-polym...](#)

[Figure 7.3 The schematic view of liquefier and nozzle in ME.](#)

[Figure 7.4 Schematic of heat transfer region in ME.](#)

[Figure 7.5 Three pressure drop zones in the nozzle.](#)

[Figure 7.6 \(a\) The gap \(B\) between the filament and liquefier walls filled w...](#)

[Figure 7.7 \(a\) Nozzle configuration in a conventional ME \(FDM\) model and \(b\)...](#)

[Figure 7.8 Die swell effect results in an increase in the diameter of the be...](#)

[Figure 7.9 Schematics of the liquefier entrance.](#)

[Figure 7.10 \(a\) Geometry and temperature zones of Serdeczny's model and \(b\) ...](#)

[Figure 7.11 \(a\) Temperature distribution at the liquefier at different times...](#)

## Chapter 8

[Figure 8.1 The relationship between four major components of materials scien...](#)

[Figure 8.2 Conventional manufacturing processes: e.g., casting.](#)

[Figure 8.3 AM powder production steps \[1\].](#)

[Figure 8.4 Schematic of cooling curves during solidification, \(a\) definition...](#)

[Figure 8.5 Fe-C phase diagram.](#)

[Figure 8.6 Continuous cooling transformation diagram for steel.](#)

[Figure 8.7 Time-temperature profile of a single-layer AM-manufactured Ti-6Al...](#)

[Figure 8.8 Critical continuous cooling transformation diagram for welded or ...](#)

[Figure 8.9 Time-temperature diagram presenting the nucleation onset of two d...](#)

[Figure 8.10 A comparative presentation of the theoretical equilibrium \(solid...](#)

[Figure 8.11 Solidification during inadequate diffusion in liquid and no diff...](#)

[Figure 8.12 Solute distribution without diffusion in the solid and dissimila...](#)

[Figure 8.13 Schematic presentation of constitutional supercooling: \(a\) parti...](#)

[Figure 8.14 Schematic presentation on the relation between the Gibbs free en...](#)

[Figure 8.15 \(a\) The figure depicting the nucleation of a sphere-shaped parti...](#)

[Figure 8.16 \(a\) Solid nucleus connected with substrate metal and liquid. \(b\)...](#)

[Figure 8.17 Schematic presentation of the Walton and Chalmers model showing ...](#)

[Figure 8.18 The graphics showing the growth characteristics and constitution...](#)

[Figure 8.19 Epitaxial growth of the solidified metal adjacent the fusion lin...](#)

[Figure 8.20 The schematic diagrams illustrate the modes of solidification pa...](#)

[Figure 8.21 Occurrence of various solidification structures related to const...](#)

[Figure 8.22 Change of the temperature in time, throughout the solidification...](#)

[Figure 8.23 Schematic of the dendrite formation/growth.](#)

[Figure 8.24 Influence of temperature gradient  \$G\$  and growth rate  \$R\$  on size an...](#)

[Figure 8.25 Formation mechanism of grains in AM: \(a\) single track, \(b\) multi...](#)

[Figure 8.26 Schematic of \(a\) Keyhole porosity. \(b\) Process and gas-induce...](#)

[Figure 8.27 Process window for LPBF manufactured Ti-6Al-4V alloy.](#)

[Figure 8.28 Schematic of balling incident appeared by coarsened sphere-shape...](#)

[Figure 8.29 Representation of balling phenomenon characterized by small shap...](#)

[Figure 8.30 The mechanism of liquation cracking in the melt pool area.](#)

[Figure 8.31 Schematic presentation of the microstructural development and ph...](#)

[Figure 8.32 Transformation-time-temperature plot for IN718 alloy \[79\].](#)

[Figure 8.33 Microstructure of Stellite 12 manufactured through laser-based A...](#)

[Figure 8.34 Effect of \(a\)  \$\alpha\$ -stabilizing, \(b\)  \$\beta\$ -isomorphous, and \(c...](#)

[Figure 8.35 The graphical presentation of ternary titanium alloys having bot...](#)

[Figure 8.36 The graphical illustration of thermal profiles.](#)

[Figure 8.37 Continuous cooling transformation curve for Ti-6Al-4v alloy \[99\]...](#)

[Figure 8.38 Micro-hardness values with respect to the secondary arms spacing...](#)

[Figure 8.39 The micro-hardness values with respect to the secondary arms spa...](#)



[Figure 8.40 Microstructure of Ti-6Al-4V manufactured by LPBF, \(a\) after stre...](#)

[Figure 8.41 Micro-hardness plot with respect to the alpha lath width for Ti6...](#)

[Figure 8.42 The property window presents yield strength vs. elongation for v...](#)

[Figure 8.43 The property window presents yield strength vs. elongation for T...](#)

[Figure 8.44 The fatigue behavior of \(a\) 316L and \(b\) LPBF-manufactured 17-4 ...](#)

[Figure 8.45 The schematic shows the breaking up of Laves phase and split-up ...](#)

[Figure 8.46 The fatigue plot shows strain amplitude vs. reversals to failure...](#)

## Chapter 9

[Figure 9.1 The production route of metal matrix composites in AM.](#)

[Figure 9.2 Schematic illustration of the collision between grinding ball and...](#)

[Figure 9.3 Geometrical presentation of the particle motion trajectory in an ...](#)

[Figure 9.4 Formation mechanism of TiC reinforced 316L matrix composite, \(a\)...](#)

[Figure 9.5 Microstructure showing the morphology of matrix, interface, and W...](#)

[Figure 9.6 The schematic diagram shows that the formation mechanism of ferro...](#)

[Figure 9.7 Schematic presentation for the formation of TiB phase from in-sit...](#)

[Figure 9.8 Schematic depiction of the formation mechanism of quasi-continuou...](#)

[Figure 9.9 Schematic presentation of the microstructural development in pure...](#)

[Figure 9.10 Schematic microstructure of the as-printed Ti-6Al-4V/MG composit...](#)

[Figure 9.11 SEM micrograph showing Ti-6Al-4V-3% B<sub>4</sub>C composite.](#)

[Figure 9.12 The schematic diagram illustrates the mechanism of Inconel-TiB<sub>2</sub>...](#)

[Figure 9.13 Demonstration of various failure approaches during compressive l...](#)

[Figure 9.14 \(a\) The influence of Marangoni flow, \(b\) TiC particles under int...](#)

## Chapter 10

[Figure 10.1 Topological and functional integrated design framework for AM....](#)

[Figure 10.2 Multidiscipline optimization \(MDO\) for a multifunctional thermal...](#)

[Figure 10.3 AM-enable design framework.](#)

[Figure 10.4 Design workflow for hybrid design solutions by topology optimiza...](#)

[Figure 10.5 Multifunctional design methodology.](#)

[Figure 10.6 AM model for product family design.](#)

[Figure 10.7 Poor and good part orientation for the avoidance of the “curl ef...](#)

[Figure 10.8 Types of support structures, from left to right: fill, lattice, ...](#)

[Figure 10.9 Guidance on the use of support structures.](#)

[Figure 10.10 Modification of circular profile to avoid “dropping effect.”...](#)

[Figure 10.11 Hollow features printed with the hollow extrusion \(a, b\) perpen...](#)

[Figure 10.12 Line-of-sight powder removal: \(a\) small radius, \(b\) large radiu...](#)

[Figure 10.13 A feature with \(a\) sharp corners and \(b\) smooth corners.](#)

[Figure 10.14 Design variations showing some thin sections that can encourage...](#)

[Figure 10.15 The three classifications of structural optimization. \(a\) Sizin...](#)

[Figure 10.16 Classification of topology optimization methods.](#)

[Figure 10.17 How topology optimization transforms the structural form of \(a\)...](#)

[Figure 10.18 Influence of volume fraction on interpolation function for SIMP...](#)

[Figure 10.19 Linear filter for a 2D mesh.](#)

[Figure 10.20 Classification of design-dependent loads for topology optimizat...](#)

[Figure 10.21 Thermomechanically loaded structures \(a\) with constant temperat...](#)

[Figure 10.22 Workflow for density-based topology optimization methods.](#)

[Figure 10.23 Initial design domain and optimized bridge-like designs with in...](#)

[Figure 10.24 Different allowable minimum self-supporting angles for satisfyi...](#)

[Figure 10.25 Element density with supporting elements in a 2D FE mesh.](#)

[Figure 10.26 Optimum designs showing difference in the topologies resulting ...](#)

[Figure 10.27 Topology-optimized half MBB beam with AM filter and Heaviside p...](#)

[Figure 10.28 Optimized designs of an aerospace bracket. The right bracket wa...](#)

[Figure 10.29 Neighboring elements to element  \$e\$  for a single layer.](#)

[Figure 10.30 \(a\) Unconstrained and \(b\) constrained topology-optimized cantil...](#)

[Figure 10.31 Some examples of 2D unit cells.](#)

[Figure 10.32 Some 3D unit cell types. \(a\) 3d Hexagon, \(b\) "X" shape, \(c\) oct...](#)

[Figure 10.33 Relationship between a lattice structure and its framework.](#)

[Figure 10.34 Lattice orientation showing Euler angles  \$\alpha\$ ,  \$\beta\$ ,  \$\gamma\$](#)

[Figure 10.35 Uniform lattice structure.](#)

[Figure 10.36 Comparison between \(a\) uniform and \(b\) conformal lattices.](#)

[Figure 10.37 Voronoi-based lattice structures. \(a\) Normal Voronoi structure,...](#)

[Figure 10.38 Design workflow of multiscale geometric modeling of lattice str...](#)

[Figure 10.39 SIMP results for 0.5 volume fraction with penalty value \(a\) set...](#)

[Figure 10.40 Representative structures with a volume fraction of 0.5. \(a\) So...](#)

[Figure 10.41 Library of surface-based unit cells: \(a\) G \(Schoen's Gyroid\), \(...](#)

[Figure 10.42 Schwarz's  \$P\$  surfaces \(for value of  \$t = 0.37\$ \); \(a\)  \$f\_P\(x,y,z\) \leq\$](#)

[Figure 10.43 Example of a linear material grading for \(a\) strut-based BCC la...](#)

[Figure 10.44 Workflow for RDM method.](#)

[Figure 10.45 Elements' centroids from strut  \$j\$ .](#)

[Figure 10.46 Screening process for RDM.](#)

[Figure 10.47 Effect of build orientation on a dogbone sample. \(a\) CAD model ...](#)

[Figure 10.48 Orientation angles for framework build showing support structur...](#)

[Figure 10.49 Angle threshold of  \$\leq 30^\circ\$  of cylindrical axis to building directi...](#)

[Figure 10.50 Maximum displacement in the framework.](#)

[Figure 10.51 Maximum residual stress in the framework.](#)

[Figure 10.52 Volume of support structure used for the build.](#)

[Figure 10.53 Residual stress and deformation plots for  \$22.5^\circ\$  rotation about ...](#)

[Figure 10.54 Inverted Y \(a\) and Y "tree-like" \(b\). structures supporting a th...](#)

[Figure 10.55 Cantilever CAD geometry supported by lattice structures.](#)

[Figure 10.56 Unit cell voxel types.](#)

[Figure 10.57 Designs with intricate features supported by minimal cellular s...](#)

[Figure 10.58 Workflow for integrated topology optimization and support struc...](#)

[Figure 10.59 Different support types compared \(Part in black and support in ...](#)

[Figure 10.60 Enhanced workflow of a topology optimization integrated support...](#)

[Figure 10.61 Workflow for redesign of aerospace bracket.](#)

[Figure 10.62 Original CAD.](#)

[Figure 10.63 Topology-optimized solution and reconstructed design.](#)

[Figure 10.64 Stress distribution of original design \(a\) and topology-optimiz...](#)

[Figure 10.65 Design domain, boundary, and load conditions.](#)

[Figure 10.66 Topology-optimized result from Altair HyperMesh.](#)

[Figure 10.67 Printed and machined structural members.](#)

[Figure 10.68 \(a and b\) Initial denture framework, \(c\) projection of X-ray sh...](#)

[Figure 10.69 Optical images of dental framework's \(a\) green state \(b\) sinter...](#)