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Narendra B. Dahotre, Mangesh V. Pantawane, and Shashank Sharma

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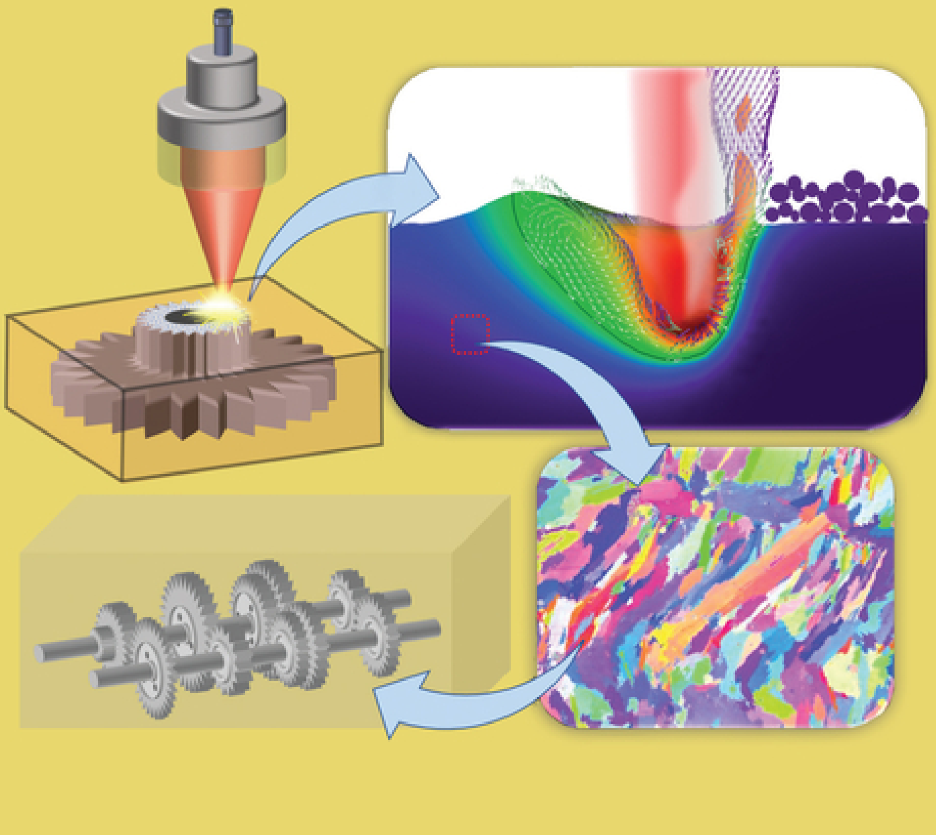
Modeling, Simulation, and Experiments



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Authors

Prof. Narendra B. Dahotre
University of North Texas
Department of Materials Science & Engineering
1155 Union Circle
Texas
United States

Dr. Mangesh V. Pantawane
University of North Texas
Department of Materials Science & Engineering
1155 Union Circle
Texas
United States

Dr. Shashank Sharma
University of North Texas
Department of Materials Science & Engineering
3940 N Elm Street
Texas
United States

Cover: © Laboratory for Laser Assisted Additive & Subtractive Materials Manufacturing, Department of Materials Science & Engineering, University of North Texas, Denton, Texas, USA

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

Print ISBN: 978-3-527-34791-9
ePDF ISBN: 978-3-527-82880-7
ePub ISBN: 978-3-527-82882-1
oBook ISBN: 978-3-527-82881-4

Typesetting Straive, Chennai, India

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Preface

Today, the manufacturing sector is witnessing the rapid growth of additive manufacturing (AM) technology, with different materials being used to produce various products and components. The use of AM techniques is now being envisioned for manufacturing components in the medical, dental, aerospace, automotive, and tooling sectors. The popularity of AM is driven by its agile and adaptive nature and its beneficial features, including its ability to produce intricate, complex, near-net parts; compositional and functional grading; custom tailoring; affordability; reduced waste and tooling costs; and single-step manufacturing. Of the different types of AM techniques developed over the years, laser-based additive manufacturing (LAM) techniques have been explored in depth for many different alloys, ceramics, and composites. LAM holds tremendous potential to expand beyond its existing capabilities by understanding and developing efficient manufacturing strategies.

While significant advancements in LAM have given us a preliminary understanding of the technique, several challenges related to processing and materials being processed are yet to be addressed. These challenges include poor consistency of parts in terms of composition and microstructural attributes; the need to control component properties, defects, dimensional accuracy; and the extended production time required to produce a single component. Consequently, conventional manufacturing techniques are still preferred over LAM for manufacturing many components. Developments in laser-based AM are primarily focused on aspects such as machine design and performance; processes and techniques; process control and sensing, including cyber-enabled AM; design, validation, verification, and quantification of AM parts; the infrastructure of AM; the supply-chain impact of AM; sustainability issues in AM; product life-cycle design; testing and adaptation; and rapid tooling. However, substantially limited emphasis has been placed on fundamental understanding of the development, characterization, and performance of tool (laser) and material interactions during and after LAM. Furthermore, due to the inherently dynamic nature of LAM (interaction times ranging from milliseconds to pico-seconds), it is challenging to realize the physical phenomena associated with the laser-material interaction zone and correspondingly evolving material attributes (microstructural, phase, and compositional) via in situ probing and measurements of thermodynamic and kinetic parameters. Given these constraints, multiphysics computational modeling based on thermophysical and kinetic aspects of laser-material interaction appeared to be the most practical approach to understanding and eventually controlling LAM for process and material property optimization.

Although the field of computational modeling of laser-material interaction has substantively evolved for laser-based processes such as cutting, welding/joining, and surface modification (alloying, coating, cladding, and texturing), it is in its infancy for LAM. In particular, multiscale modeling and simulation of LAM in view of materials science are severely lacking due to the complex thermokinetic evolution associated with this multi-laser track, multi-layer process. Without further concentrated efforts to understand and control the evolution of material attributes (microstructural, phase, and compositional), LAM technology will continue to produce components with dimensional complexity and accuracy but inferior mechanical, chemical, and functional properties.

This book provides a fundamental, systematic understanding of the laser-material interactions during multi-laser track, multi-layer LAM in an effort to position it for adoption in a wide range of materials systems (alloys, ceramics, and composites) and applications beyond the current state of the art. These efforts are also expected to trigger minds around the world to dive deeper into LAM. The book describes various approaches for understanding materials processing fundamentals during LAM via computational modeling and simulations. These approaches help build a fundamental understanding of computational materials science and help recognize its potential for controlling LAM to achieve the desired outcome. Given the significance of laser-material interactions in LAM, physical phenomena associated with these interactions are discussed in detail to emphasize the crucial part they play. Understanding these physical processes is elucidated through their effects on compositional, phase, and microstructural evolution within the material and resultant mechanical, chemical, and functional properties of components manufactured via LAM. The effects of various laser processing and material precursor parameters on the resulting material (component) attributes, including mechanical and surface (physical) texture, are also part of the book. Whenever possible, each aspect related to materials science is presented through multiscale modeling and simulation approaches supplemented with appropriate experimental/practical observations.

The attributes of AM are described sequentially in six chapters. Chapter 1 provides a brief introduction to conventional manufacturing techniques followed by broader definitions of AM in general and LAM in particular. The chapter also introduces the advantages of AM over conventional manufacturing along with current challenges associated with AM and the importance of computational modeling in AM. Chapter 2 introduces the concept of computational materials science and the length and time scales of these concepts as they have evolved so far. This chapter also provides a brief overview of the current state of computational materials science in AM. The complexity, accuracy, and utility of any computational model depend on the details of the physical processes conceived, understood, and incorporated in the model. Hence, Chapter 3 discusses topics such as the conversion of laser light energy to heat, modes of heat dissipation, and dynamics of the melt pool. As a logical progression, Chapter 4 explores the microstructural and mechanical aspects of LAM integrated with computational modeling. This integration is provided through evolution and/or predictions of solidification morphologies, microstructural features, and resultant mechanical properties. The effects of AM process parameters and strategy on the evolution of these attributes are also discussed. Any manufacturing technique such as AM involving a thermal source or process is also likely to affect the thermal stresses and physical texture of the component being manufactured. Chapters 5 and 6 provide insight into the evolution of these aspects in terms of LAM process parameters and the design of potential controls through computational modeling.

The authors, NBD, MVP, and SS, are deeply grateful to all those working in the fields of laser-material interactions and AM whose work and literature were the primary source and inspiration in developing the concepts and content of this book. We also thank our colleagues and mentors for inspiring us to follow this interesting and exciting path. Last but not least, we are forever indebted to our family members, without whose moral support efforts of such complexity and magnitude would not be possible.

Denton, Texas, USA
October 28, 2021

Narendra B. Dahotre
Mangesh V. Pantawane
Shashank Sharma

Acronyms

AM	Additive Manufacturing
ALPD	Automated laser powder deposition
CA	Cellular automata
CAD	Computer-aided design
CCA	Classical cellular automata
DFT	Density functional theory
FEM	Finite element method
GCA	Generalized cellular automata
HF	Hartree-Fock
ICME	Integrated Computational Materials Engineering
KMC	Kinetic Monte Carlo
LAM	Laser-based additive manufacturing
LC	Laser consolidation
LDED	Laser-based direct energy deposition
LENS	Laser engineered net shaping
LMF	Laser metal forming
LPBF	Laser powder bed fusion
LPD	Laser direct casting
MC	Monte Carlo
MD	Molecular dynamics
SDM	Shape deposition manufacturing
SLA	Stereolithography
STL	Standard Triangulation Language or Standard Tesselation Language

1

Introduction to Additive Manufacturing

Every human-made object around us has a unique history. This history is the evolution of raw materials that are extracted from the earth through human intervention and made into a usable form. The development of humankind has always been linked to modifying the history of raw material evolution into a usable product (manufacturing) in the pursuit of making it more efficient and flexible. Today, in the early decades of the twenty-first century, additive manufacturing (AM) is the most advanced and cutting-edge technique used in manufacturing. It entered the limelight as '*3D printing*' and has flipped the tables in research and development with a paradigm shift, gradually ushering in the fourth Industrial Revolution. However, we can only recognize the full worth of AM by understanding traditional manufacturing techniques and their evolution. This chapter first presents the history of manufacturing and the AM approach. It addresses the advantage of AM over conventional manufacturing while considering the challenges AM currently faces. The remainder of the chapter introduces laser-based AM, which is at the forefront of AM techniques. Overall, understanding the fundamental aspects of these techniques and their effects is the primary goal of this book.

1.1 Evolution of Manufacturing

Manufacturing is the process of forming a usable product out of raw materials using manual labor or mechanical machinery. The archaeological evidence for manufacturing dates back to the Stone Age, when *Homo habilis* produced the earliest tools carved out of stones [De la Torre, 2011]. This record suggests a subtractive manufacturing technique, where material is removed from a single piece to transform it into another usable form. Other techniques emerged progressively, including joining, machining, casting, and transformation (deformation) of materials. However, these processes were carried out by hand at a small scale to produce household commodities.

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With the addition of machines, the scale of manufacturing surged dramatically during the first Industrial Revolution, which began in European countries in the eighteenth century and later spread to other parts of the world [Deane, and Deane, 1979]. This phase mainly centered around technologies that extracted metals (cast iron) from their natural forms (ores) and produced final products using industrial equipment. The improvement in the quality and characteristics of materials for the new types of applications and continuous production via conveyor equipment led to the second Industrial Revolution in the late nineteenth and early twentieth century [Popkova et al., 2019]. With the invention of techniques such as the Bessemer process to produce steel and electromagnetic rotary devices to electrify the technology, this phase was a technological revolution [Mokyr, 1998]. The second half of the twentieth century was driven mostly by renewable sources of energy and the emergence of digital technologies, constituting the third Industrial Revolution [Popkova et al., 2019]. The progress and features of the Industrial Revolutions are illustrated in Figure 1.1.

Today, in the early decades of the twenty-first century, AM is an integral part of the ongoing fourth Industrial Revolution. This new technological mode of manufacturing offers broad flexibility for materials science, process development, and structural design. Using AM, intricate and complex parts can be manufactured with the desired quality, which would be extremely challenging using earlier subtractive (machining) and formative (casting) manufacturing modes. Moreover, the inherent nature of AM is leading manufacturing toward fully automated digital manufacturing through robotic equipment. In contrast to earlier manufacturing techniques, which steadily evolved and advanced in response to challenges experienced by earlier versions, AM is an entirely new technique. Therefore, AM may be considered not an evolution but

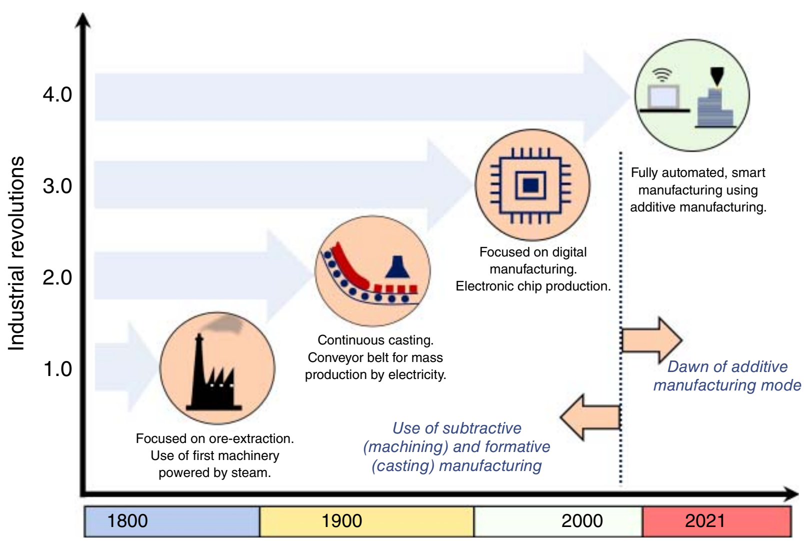

Figure 1.1 Timeline of the Industrial Revolutions.

the dawn of a new manufacturing era. Before diving deep into the technical features and current status of AM, we examine its intriguing fundamental nature in the following section.

1.2 Concept of AM

Although AM seems to be a new manufacturing mode in the twenty-first century, it existed silently as an auxiliary manufacturing technique for several decades in the previous century. The origin of all metallic AM types can be traced back and linked to welding and surface coating techniques. For instance, the friction stir AM technique evolved from friction stir welding and processing. These auxiliary manufacturing techniques were mature and only required a trigger to evolve into AM.

Eventually, AM was conceived as a fabrication method in the polymeric system in 1981 by Hideo Kodama, from Japan [Kodama, 1981]. He developed and demonstrated a prototype of the automatic fabrication of intricately shaped polymers, using layer-by-layer curing of the liquid and photo-hardening the polymer with ultraviolet rays. An intricate relief map of the mountain fabricated by Kodama using transparent polymer is presented in Figure 1.2. Charles Hull later advanced this technique and patented it as stereolithography (SLA) [Hull, 1984]. The concept of layer-upon-layer fabrication was then coupled with existing metallic welding and surface coating techniques, which led to the emergence of various metallic AM techniques.

The American Society for Testing and Materials (ASTM, an international standards organization primarily involved in developing and publishing voluntarily consensus technical standards for a broad range of materials, techniques, services, products, and systems), as per ISO/ASTM 52900:2015 (E), defines AM as “a process

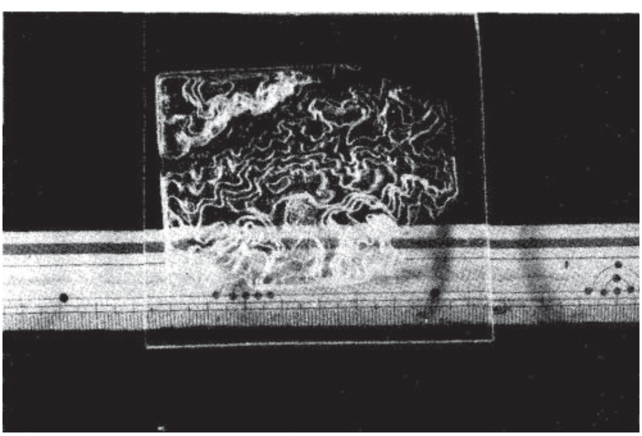

Figure 1.2 An early 3D fabrication via AM: a relief map of mountains using transparent polymer [Kodama, 1981].

of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [ASTM Standard, 2015]. Any material in its pure continuum/bulk form is held together by atomic bonds; for example, metal/alloys are bonded by metallic bonds, polymers by covalent and Van der Waal bonds, ceramics by ionic or covalent bonds, and composites by any combinations of these bonds. AM involves joining the material using a distinct physical phenomenon associated with an energy source that leads to the formation of such primary atomic bonds. The energy source can be in any of multiple forms (laser beam, electron beam, ultrasound, or friction); it is transformed into heat or a combination of heat and mechanical energy that joins the material through a primary atomic bond. This joining takes place at a micro- to macro-dimensional scale, depending on the type of energy source and the size and shape of pieces of unjoined material. These pieces of material in a feedstock[1] can be in forms such as powder (spherical particles), wires, rods, bars, and sheets. A moving interaction zone of energy and feedstock forms a single consolidated or joined track/line of material. The successive joining of such tracks in a single plane forms a fabricated layer of a given material. Eventually, this layer-upon-layer consolidation results in a three-dimensional component, and hence the name *additive manufacturing* was coined.

AM allows the flexibility of fabricating any intricate shape that can be created with the aid of CAD (computer-aided design) software. A virtual model of the part to be fabricated is converted into an STL[2] file format, which presents the geometry in a form the AM machines can understand to build the physical part. The STL file allows the AM machine to read the path of the interaction zone of energy and feedstock in a given layer as well as the dimensions and the number of layers to fabricate the geometry encrypted in the STL file. Given this path and the geometric dimensions, the machine allows the user to choose processing parameters such as power and the speed of the moving energy source. The feedstock provides additional flexibility depending on the material type, shape, and size distribution.

The various components of AM provide tremendous flexibility, and their combination can lead to multiple possible fabrication outcomes. These features of AM are as follows:

- Type of energy source
- Physical phenomenon
- Type of material (metal, ceramic, polymer, composite)
- Type of feedstock (shape, size, and distribution)
- Means of distributing the feedstock to interact with the energy source (already laid feedstock and simultaneous deposition of energy and feedstock)
- Combination of processing parameters (power of energy source, speed and path of energy-feedstock interaction zone, and feedstock input)
- Composition of material (alloy development)

1 A bulk of raw unjoined material that is consolidated/joined via AM to yield a final form.
2 This acronym is derived from STereroLithography. It is also sometimes defined as Standard Triangulation Language or Standard Tesselation Language.

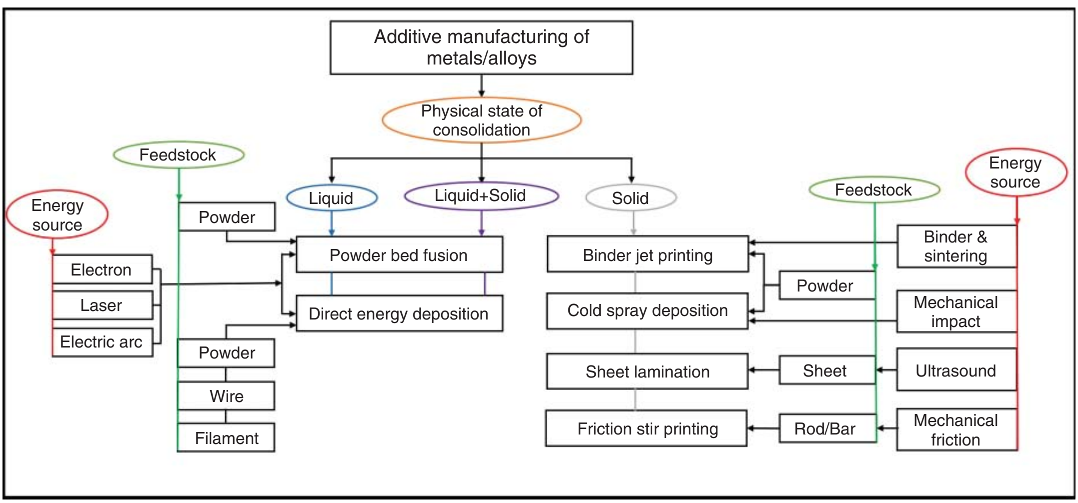

Figure 1.3 Classification of various AM techniques.

Categorization-These features also provide multiple bases for classifying different AM processes. As per ASTM/ISO standards, AM processes have the following seven categories:

- Binder jetting
- Directed energy deposition
- Material extrusion
- Material jetting
- Powder bed fusion
- Sheet lamination
- Vat polymerization

As mentioned earlier, the classification can have multiple forms based on various fundamental features. However, at this point, the reader should bear in mind the scope of the current book, which focuses on the AM of metals/alloys. There are multiple ways to classify the AM of metals and alloys, including classification based on the physical state of consolidation, energy source, feedstock, feedstock input, etc. Classification based on the physical phenomena governing the physical state of consolidation is useful from a materials science perspective. This is because the process-associated physical phenomena substantially control various properties of the AM-fabricated component. This classification based on the physical state of consolidation also considers the type of feedstock and the energy source, as shown in Figure 1.3.

1.3 Advantages over Conventional Manufacturing Techniques

Needless to say, the fundamental difference between AM and conventional manufacturing is due to their distinct processes and fabrication steps leading to the final component. Following are the key features that separate AM from conventional manufacturing.

- *Material efficiency*: The prime functional difference between these approaches arises from the substantially high material efficiency associated with the AM process, whereas conventional manufacturing results in more material loss through the subtractive approach in multiple steps.
- *Complex parts*: The layer-upon-layer approach of AM allows the fabrication of complex geometries, which are nearly impossible or highly challenging to fabricate using a conventional approach in a single processing step.
- *Assembly stage*: Traditionally, a moving system is required to manufacture in stages, first fabricating each component of the system and then assembling them. AM merges manufacturing and assembly into a single step, making a more efficient fabrication chain.
- *Customized printing*: AM provides the freedom to conceive any imaginable shape and make it a reality. In addition, customization through a digital interface allows

personalized products to be made for individuals. Conventional manufacturing does not provide such customization or the freedom to fabricate any shape.
- *Thermokinetic flexibility*: Most AM techniques provide process flexibility and, in turn, thermokinetic flexibility to derive the desired mechanical output from the process, whereas conventional techniques have limited options to vary the thermokinetics in a single step.

Presently, many AM techniques are available, and more are emerging. Among these AM techniques, laser-based AM (LAM) techniques are being widely explored, substantially impacting the research and industry sector. The laser is a rapidly steerable and effective energy source that provides high energy density in a micro-region. This allows microscale feedstock (powder and wire) to rapidly melt and solidify, leading to micro-volume consolidation of feedstock. Therefore, the type of energy source and feedstock used in LAM allow the rapid fabrication of complex geometry with the desired surface finish while providing increased efficiency in both cost and materials. LAM is also a single-step process that provides considerable flexibility through a broad processing window that can monitor the thermodynamic state, morphology, and distribution of the phases as well as the crystallographic and physical texture (surface roughness) of the printed component. The most commonly employed and investigated LAM techniques for fabricating metal/alloys are laser powder bed fusion (LPBF) and laser-based directed energy deposition (LDED). The fundamental principles and operation of these techniques are introduced in the following section.

1.4 Laser-Based AM

Recent advances in design and operation have led to numerous LAM techniques. They vary mostly based on the type, size, and delivery of the feedstock to the laser source. Despite these variations, a few physical phenomena associated with the process can be identified. Thus, LAM techniques can be classified as LPBF and LDED processes.

1.4.1 Laser-Based Directed Energy Deposition

LDED is also referred to as the direct metal deposition (DMD) technique, which evolved from the laser cladding technique in the late twentieth century [Koch, and Mazumder, 1993, Mazumder et al., 1997]. In LDED, the feedstock (usually a powder or wire) is delivered through a nozzle directly to the focal plane of the laser beam, as depicted in Figure 1.4. The powder is carried from the powder feeder via carrier gas, often coaxially focused at the focal region of the laser beam. As the name suggests, the purpose of the carrier gas, such as argon or nitrogen, is to carry the powder to its destination with sufficient momentum to hit the laser beam focal plane. Under the high power density of the laser beam at the focal plane, the powder instantly melts and falls onto the substrate, where it solidifies. This follows the fabrication of a layer through metal deposition via multiple laser tracks, and successive layer-upon-layer

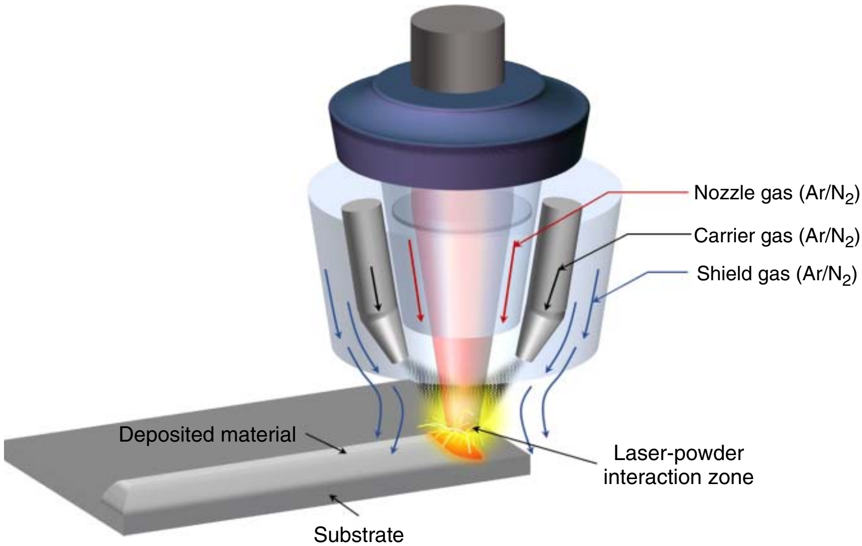

Figure 1.4 Schematic representation of the LDED operation using powder feedstock.

fabrication allows the formation of a 3D component. In most LDED machines, the substrate attached to the stage has three-axis (X, Y, and Z) freedom, while the laser head with the coaxial powder feeder remains stationary. The relative motion between the laser heat source and the stage leads to multiple laser tracks, and the layer thickness in the build direction is monitored by the STL file fed to the LDED machine.

The STL file allows the AM machine to monitor the three-axis stage movement with respect to the laser head. Nozzle gas (Ar/N_2) is often supplied to prevent damage to the laser optics caused by spatter ejected in the feedstock-laser interaction zone at the focal plane region. In addition, shield gas (Ar/N_2) prevents the feedstock-laser interaction zone and melt pool[3] region from oxidation. For most non-reacting (not easily oxidized) metals/alloys, shield gas is sufficient to prevent oxidation. However, such an assembly may not be able to prevent the oxidation of metals that have a high affinity for oxygen, such as Ti and Al. The fabrication of these alloys is often carried out in a closed chamber where oxygen activity can be set to as low as 50 ppm to reduce oxidation. Laser engineered net shaping (LENS) machines by Optomec provide a sealed assembly to fabricate oxidation-prone alloys via LDED.

The type of feedstock (powder or wire) can be varied in size depending on the delivery system to the laser beam source and laser characteristics such as wavelength, intensity distribution, beam diameter, etc. Such variations in the laser beam and feedstock (size and type) can lead to different dynamics, while the physical phenomena remain the same. Before the ASTM/ISO categorization

3 The melt pool is the melted region that results from heating by any heat source, surrounded by the solid material.

of this technique as a directed energy deposition, several names were introduced by researchers and companies trying to develop closed-loop machines. These names included LENS [Atwood et al., 1998], laser metal forming (LMF) [Gäumann et al., 2001], laser consolidation (LC) [Xue et al., 2000], laser direct casting (LDC) [Hand et al., 2000], automated laser powder deposition (ALPD) [Toyserkani, and Khajepour, 2006], shape deposition manufacturing (SDM) [Fessler et al., 1996], and so on. Although these processes had different names, their underlying principle was the same.

1.4.1.1 Machine Design

Modern evolving LDED machines have multiple degrees of freedom with the development of machine design; for instance, a five-axis stage system attached to the substrate. In contrast to the stationary (three-axis) stage, the five-axis system allows rotation of the stage; thus, support structures[4] are not required during fabrication [Liu et al., 2017]. In addition to stage rotation, the moving laser further augments the degree of freedom during fabrication, thereby allowing control over physical texture (surface roughness) and complexity of the component. In the LDED machine, the feedstock can be fed through either a coaxial nozzle or an off-axis lateral nozzle focusing at the laser beam focal plane. A powder-fed LDED machine can have single or multiple nozzles to eject the powder at the focal plane of the laser beam [Mazzucato et al., 2017]. Multiple nozzles with the appropriate use of inert gas lead to improved deposition efficiency by reducing the amount of unmelted powder, as it does not enter the laser-powder interaction zone and falls in the vicinity of the fabricating component. Moreover, multiple nozzles can eject different metal powders at different rates, allowing the fabrication of functionally graded components [Mahamood, and Akinlabi, 2015]. Furthermore, the substrate in LDED can be preheated to change the thermokinetics, especially the thermal gradients associated with the process [Corbin et al., 2018].

1.4.1.2 Process Parameters

Laser. In LDED, the laser is the source of energy used for the consolidation/joining (melting followed by solidification) of the feedstock. Different types of lasers can be employed in LDED fabrication, including Nd:YAG, CO_2, excimer, and fiber lasers. A Yb-doped fiber laser is most commonly employed after solid-state Nd:YAG laser in laser-based AM. Yb-fiber laser, usually pumped by the diodes in a 950-980 nm wavelength, can have an output wavelength in the near-infrared region ranging from 1030 to 1090 nm in a continuous wave or pulse wave mode. Every metal and alloy has a distinct light absorption coefficient at a given wavelength of light, determining the actual laser energy absorbed for melting. In LDED, laser parameters such as the laser power, laser beam diameter, laser intensity distribution (Gaussian or top-hat distribution), speed at which the laser beam moves relative to the substrate, and moving path can be easily varied and optimized to achieve the desired set of characteristics

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4 Support structures are often incorporated in the STL file. However, they are not part of the actual 3D component. Support structures are often printed to the main component during fabrication to prevent part deformation and to ensure that it is attached to the substrate.

of a given material to be fabricated. The diameter of laser beam in LDED is often in the range of 0.5 to 5 mm, while the laser/stage moving speed varies from 5 to 20 mm/s. The laser power employed in LDED is usually high, in the range of 300 to 4000 W. Such a combination of process parameters yields a very high deposition rate in LDED.

Feedstock. Powder is most often used as a feedstock in LDED machines as it can fabricate small complex parts with high geometrical accuracy due to its micron-level size (40 to 120 μm). Such micron-sized powder allows the fabrication of thinner parts and simultaneously improves surface roughness. In addition, as discussed earlier, functionally graded material can be explored by feeding powder through multiple nozzles. However, this feedstock has several downsides, such as the high cost of powder preparation, health hazards, and significant loss of material during fabrication.

On the other hand, wire as a feedstock provides highly efficient material fabrication. Moreover, the production of wire feedstock is a simple, cleaner, cheaper process, and handling the wire is not hazardous. The wire is fed through the coaxial nozzle or the off-axis lateral nozzle, focusing at the laser beam focal plane. The diameter of the wire used for LDED feedstock ranges from 1 to 1.5 mm, which restricts the fabrication of thinner components, and the surface roughness is comparatively higher than powder-fed LDED [Rodrigues et al., 2020, Fu et al., 2021, Froend et al., 2018]. In contrast to powder feedstock, wire-fed LDED can be explored for underwater fabrication [Fu et al., 2021]. Nevertheless, wire-fed LDED is widely studied for its unique processing features.

The machine design features and process parameters associated with LDED provide tremendous flexibility to govern the thermokinetics, thermomechanics, and fluid dynamics of the process. These process-inherent physical phenomena affect microstructures; phase transformation; one- and two-dimensional crystallographic defects such as dislocations, twins, and stacking faults; grain/phase interfaces; and three-dimensional defects, including cracks and pores. These aspects, in turn, impact the mechanical and surface properties of the material. Thus, it is essential to know the degree of flexibility provided by the given LAM machine design and process parameters. These machine design and process parameters are detailed in Figure 1.5. The following chapters discuss the effect of machine design and process parameters on the microstructural characteristics listed previously with the aid of computational simulations.

1.4.2 Laser Powder Bed Fusion

LPBF is a widely studied LAM technique. As the name suggests, the feedstock in LPBF is limited to powder, mostly in the range of 10 to 45 μm. Unlike in the LDED technique, the feedstock (powder) is first spread onto the substrate as a thin layer that ranges from 10 to 100 μm. The laser selectively scans this layer. At the location scanned by the laser, the powder instantly melts and solidifies, thereby consolidating the scanned region. The substrate moves down within a hollow cylinder to occupy the powder for subsequent layer deposition. The unmelted powder surrounding the fused region provides support for the subsequent layer. When another layer is spread

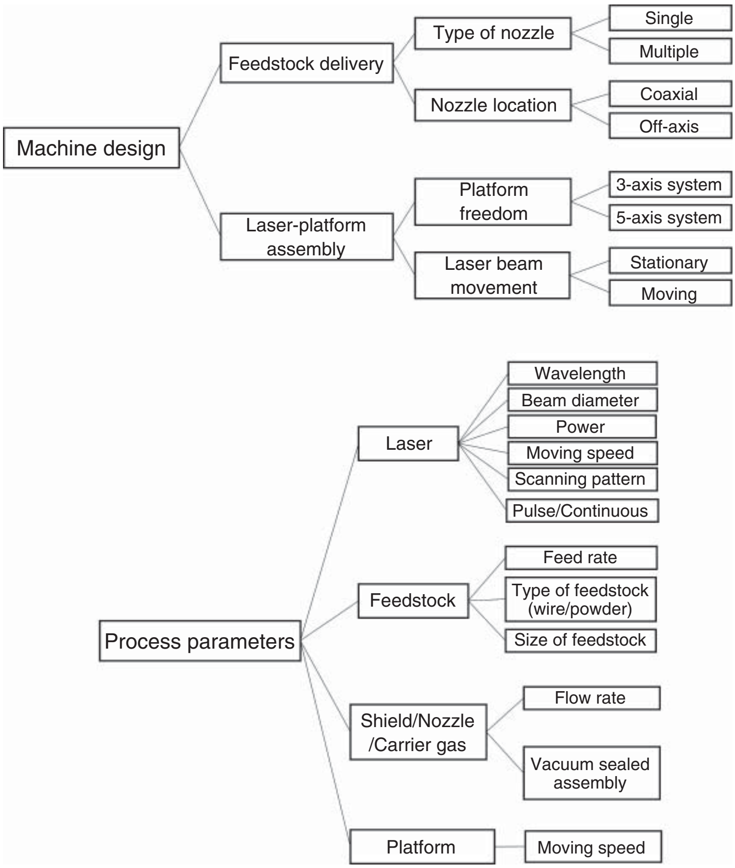

Figure 1.5 Machine design and process parameters associated with LAM.

onto a previously fused layer, the new layer is again scanned by the laser. The process continues until the desired component is built. The LPBF process is illustrated in Figure 1.6.

1.4.2.1 Process Parameters

The laser beam diameter in LPBF can vary from 30 to 600 μm, while the laser scanning speed can be as high as 200 to 4000 mm/s. The laser power varies in a range of 100 to 500 W. The resulting volume of the melt pool generated during LPBF is usually smaller than that of LDED. Therefore, the deposition rate in LPBF is often lower than that of LDED. However, LPBF produces a superior surface finish for the printed component than LDED. The smaller volume of the melt pool produced in LPBF also allows the fabrication of components with greater intricacy at the micron level. All of these process parameter differences in LDED and LPBF are summarized in Table 1.1.

The machine and process design in LPBF do not allow the powder stage to have any axis of freedom, unlike the three-axis and five-axis freedom in the LDED process.

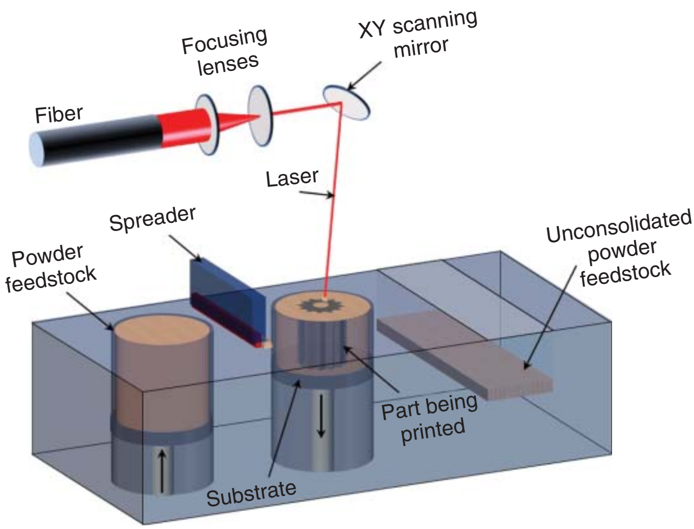

Figure 1.6 Schematic representation of a laser powder bed fusion process.

Table 1.1 Comparison of the processing parameters involved in the LDED and LPBF processes.

Parameters	LDED	LPBF
Laser power (W)	300–4000	100–500
Scanning speed (mm/s)	5–20	200–4000
Laser beam diameter (μm)	500–5000	30–600
Deposition rate	High	low
Surface finish	Moderate	Superior
Feedstock	Wire, powder	powder
Powder size (μm)	45–120	10–45

Source: [Bian et al., 2017]

The stage freedom in LDED allows variable thermokinetics in different directions. Nevertheless, a similar effect can be achieved in LPBF by varying the orientation of the component to be printed with respect to the build direction. For instance, a cylindrical component can be printed in different orientations with respect to the constant build direction, as illustrated in Figure 1.7. The printing component can be oriented to allow heat extraction in the desired direction, which, in turn, governs the crystallographic texture within the component.

Additionally, the powder bed stage in LPBF can be heated to any temperature at the beginning or any time during fabrication, allowing superior control over the thermokinetics of the process. The powder bed is often heated to reduce the thermal gradient, thereby reducing induced thermal stresses to avoid the formation of thermal cracks. Heating during the powder bed stage provides

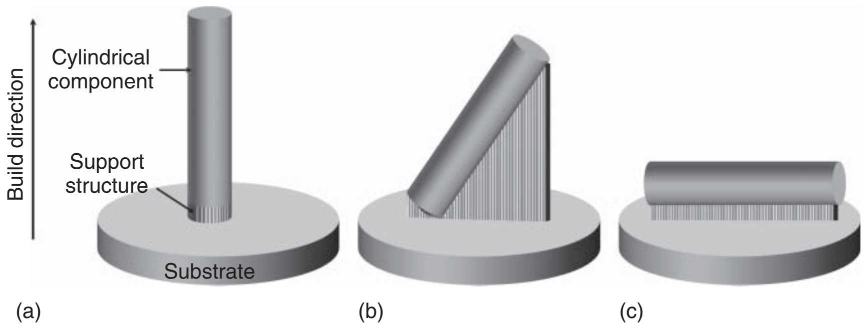

Figure 1.7 Different ways of printing a cylindrical component via laser powder bed fusion.

tremendous thermokinetic control, which, in turn, influences the thermodynamic state (equilibrium/non-equilibrium) of the phases formed during the process.

1.4.3 Estimation of Energy Input in LAM Processes

When optimizing fabricated parts for various properties, recognizing the energy input of the given LAM process is important. Energy input must consider the laser processing parameters to yield the energy density needed to fabricate the material. In the LDED process, the laser energy input is presented in multiple forms. One of them is the power density, also known as irradiance (W/m^2), which can be obtained as

$$\textit{Power Density or Irradiance} = \frac{P}{A} \tag{1.1}$$

where P is the laser power (W) and A is the cross sectional area (m^2) of the laser beam exposed to the material.

Residence time (t_r) is another helpful parameter considered in multiple energy input representations. It is simply the duration for which a laser beam is exposed to a single location while scanning the sample. This can be calculated using the laser beam diameter (D) and laser scanning velocity (V_s):

$$t_r = \frac{D}{V_s} \tag{1.2}$$

Another way to represent energy input is laser fluence (F), which is energy density. Laser energy fluence can also be defined as a time-integrated energy flux. Therefore, the residence time is helpful to obtain the energy density/laser fluence:

$$F = \frac{P \times t_r}{A} \tag{1.3}$$

In addition, linear energy density (LED) (in J/m) is also considered as a parameter during property optimization and can be obtained as

$$LED = \frac{P}{V_s} \tag{1.4}$$

For the LPBF process, while the previous energy input parameters are appropriate, most researchers use volumetric energy density as the energy input parameter, considering the layer thickness (d) and hatch spacing (h). This volumetric energy density (VED) is calculated as follows:

$$VED = \frac{P}{V_s \times h \times d} \tag{1.5}$$

However, the energy parameter *VED* bears some limitations, as identified by several studies [Scipioni Bertoli et al., 2017, Caiazzo et al., 2020, Prashanth et al., 2017, Ferro et al., 2020]. Some of these studies have recognized another way to represent VED by following Eq. 1.6:

$$VED = \frac{P}{V_s \times h \times D} \tag{1.6}$$

While several energy parameter representations exist, none can represent the kinetics and physics associated with the process. Each of these parameters is significant in optimizing and designing various features of the components and their characteristics.

LAM processes assisted by the pulse wave (PW) laser beam entail additional parameters as their energy transfer mechanism differs from that of a continuous-wave laser beam. A pulse laser provides considerable flexibility with its additional parameters. These parameters can be conveniently understood through the energy transfer mechanism of the pulse laser shown in Figure 1.8. In contrast to a continuous-wave laser, which delivers constant power P as indicated by the dotted red line, the pulse laser transfers energy in controllable intervals (Figure 1.8). This involves the pulse on time (t_{on}) when it delivers the power and the pulse off time (t_{off}) when power = 0. Thus, the pulse energy E_{pulse} is given as

$$E_{pulse} = \int_0^{t_{on}} P(t)dt \tag{1.7}$$

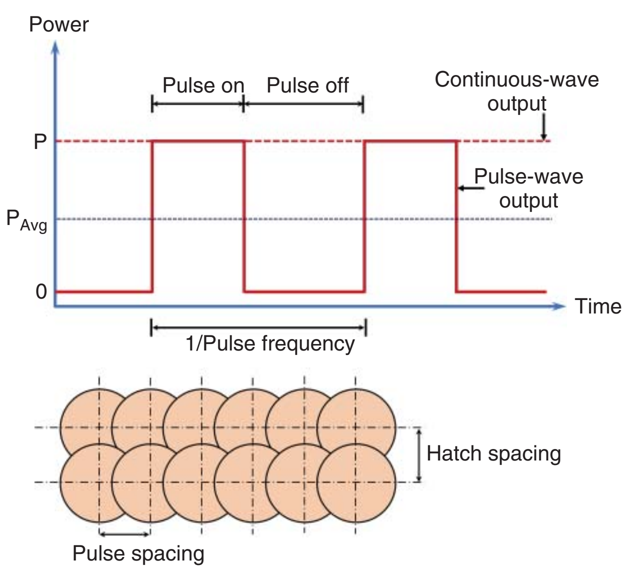

Figure 1.8 schematic of the temporal and spatial characteristics of pulses.