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Introduction and Overview

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Additive manufacturing generally denotes scalable fabrication (printing) of 3D components and structures for industrial production. Employing a layer-by-layer or voxel-by-voxel approach, additive manufacturing has started to shift the manufacturing paradigm and revolutionize the way components are produced. It not only offers unparalleled design freedom and efficiency for creating complex geometries, but also opens the door to the production of lighter, stronger, multifunctional, and multimaterial parts [1]. Its versatility knows almost no bounds; nearly all types of materials can be transformed into intricate 3D components through additive manufacturing, including polymers, ceramics, metals, composites, and even natural materials. With the vast global market of metal component production and the extensive use of metallic materials in diverse industrial sectors, there has been a surge in interest of *metal additive manufacturing* particularly over the past decade [2–4].

Metal additive manufacturing approaches can come in two key forms: fusion-based (i.e., beam-based) and solid-state (i.e., nonbeam-based) methods, both with their distinctive advantages. The former fundamentally relies on selective melting and rapid solidification to progressively build a structure, while the latter harnesses a high strain rate, extensive plastic deformation, or thermally induced atomic diffusion to metallurgically bond the material to build a structure. Fusion-based approaches, including powder bed fusion (e.g., selective laser melting [SLM] and e-beam melting [EBM]) and directed energy deposition (DED) (e.g., laser engineered net shaping [LENS] and wire arc additive manufacturing [WAAM]) have been the primary focus of industry and academia at the time of writing. This is not surprising, as much of the processes and equipment are based on similar fusion-based welding processes widely applied in the industry for decades. Similar to casting [5] and fusion welding [6], both of which are bulk-scale melting–solidification manufacturing processes, fusion-based additive manufacturing is challenged by porosity, residual stress, and hot cracking [7]. Compared to

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casting, the additive nature exacerbates these issues because of the small molten pool size, large thermal gradient, and rapid cooling rates. Additionally, epitaxial solidification leads to the natural formation of textured, columnar grain structures along the build direction, presenting a hurdle for microstructure and isotropy control [8]. These issues also limit melt-based methods to weldable alloys.

These critical issues stem from the melting and solidification nature of fusion-based additive manufacturing and can be avoided if melting is not present in the process. This motivates the development of a series of emerging nonbeam-based, solid-state processes for metal additive manufacturing – which is the focus of this book. The cutting-edge solid-state technologies explored in this book encompass cold spray additive manufacturing (CSAM), additive friction stir deposition (AFSD), ultrasonic additive manufacturing (UAM), and sintering-based processes like binder jetting additive manufacturing (BJAM) and material extrusion-enabled metal additive manufacturing (MEAM).

This relatively new field of manufacturing technologies is continuing to develop at a fast pace along with a growing wealth of research articles and white papers. The aim of this book is to present the principles and effects of the physical phenomena that each solid-state additive manufacturing method is built upon, as well as an in-depth picture of the process fundamentals, the resulting microstructures and properties, and the key industrial applications. Starting with an overview and historical perspective of metal additive manufacturing, this chapter proceeds to offer frameworks for categorizing solid-state additive manufacturing methods based on bonding mechanisms and relationship between building and consolidation. It then discusses the potential and limitations of nonbeam-based, solid-state metal additive manufacturing methods, which are implemented through deformation-based or sintering-based approaches. Furthermore, the chapter outlines the structure of the book, providing a glimpse of the topics of all the following chapters.

1.1 Overview and History of Metal Additive Manufacturing

Offering a “disruptive” concept that enables greater design freedom, rapid prototyping, and the production of complex geometries that were previously unachievable, metal additive manufacturing has enormous potential for enhancing performance such as strength and durability, weight and waste reduction, customization, as well as on-demand production and supply chain risk reduction. It has found applications in aerospace, space, automotive, defense, healthcare, and many other industries, driving innovation and reshaping the manufacturing landscape. Based on different material feeding and bonding mechanisms, metal additive manufacturing can be implemented by SLM, selective EBM, LENS, WAAM, CSAM, BJAM, UAM, and AFSD. Depending on the process, the feedstock can be in the form of powder, wire, sheet/foil, and solid bar. The first four technologies are based on melting and rapid solidification, and are thus termed “fusion-based” or “beam-based.” The last four are based on solid-state processes without melting; they are the focus of this book.

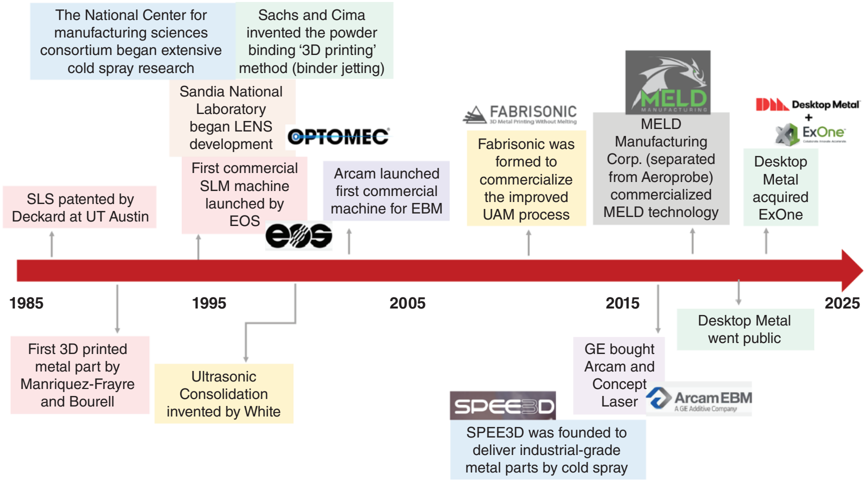

Figure 1.1 A brief history of metal additive manufacturing development over the last 40 years.

As illustrated in Figure 1.1, the history of metal additive manufacturing dates to the 1980s when additive manufacturing, in general, was in its early stages. Similar to the case with other technologies, different terminologies were invented and used for different additive manufacturing processes as they developed. Selective laser sintering (SLS) was patented by Carl Deckard in 1986 [9], the first 3D printed parts were demonstrated by Manriquez-Frayre and Bourell in 1990 [10], and Electro Optical Systems (EOS) introduced its initial SLS machine in 1995. On the other hand, the first SLM patent was issued in 1995 by the Fraunhofer Institute Institut für Lasertechnik (ILT) in Germany, eventually leading to SLM Solutions Gesellschaft mit beschränkter Haftung (GmbH) in the early 2000s [11]. SLM or SLS falls under the category of powder bed fusion additive manufacturing.

Another significant technology within the powder bed fusion category is selective EBM, patented by Larson in 1993 [12]. In 2002, the first commercial EBM machine was launched by Arcam, which was later acquired by General Electric (GE) in 2016. Enabling the fabrication of complex geometries with high spatial resolution, powder bed fusion has emerged as one of the leading metal additive manufacturing technologies today.

LENS represents another important example that leverages high-energy laser beam for metal additive manufacturing [13]. LENS involves melting and fusing nozzle-delivered metal powder onto a substrate in a layer-by-layer fashion to create intricate 3D components. The technology was patented by Sandia National Laboratories in 1994 and later commercialized by Optomec in the early 2000s. LENS belongs to the category of DED, where the material is fed in powder form.

Another notable technology in this category is WAAM. The roots of WAAM can be traced back to the 1920s when Baker proposed using an electric arc and filler wires to deposit metal ornaments [14]. In the welding industry, arc welding, laser welding, and electron-beam welding are widely used for cladding of large-scale structures and rebuild of aircraft turbine rotor tips. They are early on primitive WAAM. In recent years, advancements in robotics, sensors, and control systems have propelled the progress of WAAM technology. Precise control of welding parameters and robotic movement has improved accuracy and repeatability, not to mention the high build rate and excellent scalability offered by WAAM.

Now let us briefly review the history of solid-state metal additive manufacturing processes, wherein the feedstock is not melted. Our first focus is on cold spray, a technology with a long history dating back to the early twentieth century. The modern "cold spray" phenomenon was discovered by Papyrin and Alkhimov in the 1980s [15, 16]. Subsequently, in 1994, the National Center for Manufacturing Sciences consortium, including companies like Ford Motor Company, GE Aircraft Engines, General Motors Corporation, the Naval Aviation Depot, and Pratt and Whitney, began extensive research on cold spray. In 2008, the US Department of Defense published the Military Standard (MIL-STD-3021), establishing cold spray standardization and best practices. A series of cold spray companies have been formed since then for technological commercialization, such as SPEE3D and Impact Innovations GmbH.

Initially called "3D printing", binder jetting works by selectively depositing a liquid binding agent onto a powder bed to bind the particles together layer by layer to create a 3D object, followed by sintering or hot isostatic pressing for densification. This technology was invented in 1993 by Sachs, Cima, Bredt, and coworkers at the Massachusetts Institute of Technology (MIT) [17], later resulting in a spin-off company, Z Corporation (ultimately acquired by 3D Systems in 2012). Extrude Hone obtained an exclusive license from MIT in 1996 and launched the industry's first commercial direct metal 3D printing machine using binder jetting in 1998. As a spin-off from Extrude Hone Corporation, ExOne was founded in 2005 and quickly became a prominent player in the additive manufacturing industry, particularly in the field of binder jetting technology provider. In 2021, ExOne was acquired by Desktop Metal, which was founded by seven cofounders (including four MIT professors) in Lexington, Massachusetts, in October 2015 and went public in December 2020.

The process of material extrusion, which is commonly referred to as fused filament fabrication (FFF) or fused deposition modeling (FDM), was originally developed by Stratasys in 1989 [18]. It is based on the extrusion of a thermoplastic polymer through a heated nozzle with a fine orifice onto a substrate and the building of a free-form 3D structure layer by layer. The combination of FDM with another well-known manufacturing method, metal injection molding (MIM), where metal or ceramic powders bound with polymeric binder are pushed into a mold, constitutes the basic principle of the MEAM [19]. Desktop Metal and Markforged (founded in 2013 in Cambridge, MA) are the two leading companies that provide 3D metal printers based on material extrusion.

UAM, initially known as ultrasonic consolidation, is a hybrid technology based on ultrasonic bonding and computer numerical control (CNC) machining. This technology was invented and patented by White in 1999 [20], who founded Solidica Inc. with the aim of commercializing UAM equipment. In 2007, a collaboration was initiated between the Edison Welding Institute (EWI) and Solidica to redesign the weld tooling, facilitating high bond quality, and accommodating very high-power machines. Over a four-year development program, the team successfully enhanced the ultrasonic horn's power delivery levels, increasing it from 2 to over 9 kW. As a result of this progress, Fabrisonic LLC was founded in 2011, aiming to further advance and commercialize the improved UAM process.

AFSD is a relatively young technology in the additive manufacturing family. It originated from the friction surfacing process [21]. Based on the principle of friction stir bonding, the feedstock in the form of a solid bar is stirred against the substrate, forming deposition tracks as it goes through severe plastic deformation at elevated temperatures under a rotating tool. Around 2008, the foundation of this technology was laid by Schultz and Creehan [22], who were previously research professors at Virginia Tech before establishing Schultz-Creehan Holdings Inc. This company later merged with Aeroprobe Corporation. The initial prototype machine was constructed by Schultz and the team at Aeroprobe Corporation in 2011 [23]. The first peer reviewed paper was published by Kandasamy in 2013 [24]. In 2018, Manufacturing of Electronically Linked Devices (MELD) Manufacturing Corporation, a separate entity from Aeroprobe Corporation, brought this technology to market under the brand name "MELD Technology."

1.2 Liquid-State Bonding Versus Solid-State Bonding

Metal additive manufacturing technologies are all based on two critical steps: material feeding and material bonding. The capabilities, challenges, and resulting material properties of each additive manufacturing technology largely depend upon the method of layer bonding and consolidation mechanism [25]. Metals can be bonded in liquid phase or solid phase. Liquid-state bonding is the mechanism for fusion-based additive manufacturing technologies, such as SLM, EBM, LENS, and WAAM. Solid-state bonding is the mechanism for CSAM, AFSD, UAM, and sintering-based processes like BJAM.

1.2.1 Liquid-State Bonding

As demonstrated through fusion welding, the formation of molten pools across the interface followed by solidification can lead to good metallurgical bonding of two metal pieces. The solidification process typically happens at the liquid–solid interface via heterogeneous nucleation, resulting in epitaxial grain growth from the solid phase into the liquid. Depending on the thermal gradient and solidification rate, which govern the undercooling, there is also a possibility of nucleation inside the molten pool, especially in the presence of nucleation agents. As the transformation from liquid to solid progresses, effective heat dissipation generated by the transformation becomes essential. This process is typically facilitated through conduction within the solid, directing heat away from the advancing solidification front. Most pure metals and alloys undergo a negative volume change when they solidify.

This solidification "shrinkage" phenomenon can impart stresses upon the as-solidified structure that may lead to solidification cracking [26].

In solidification of alloys other than pure metals, the local temperature profile leads to solute redistribution and segregation of alloying and/or impurity elements. This can result in continuous alteration in composition between the liquid and solid in contact at the solidification front. If the solid phase does not have adequate time to reach its equilibrium composition, which is common in fusion-based additive processes, such redistribution results in localized variations in the composition within the solidified structure. This can lead to spatially dependent liquidus temperatures and significant constitutional supercooling, even if the liquid is hotter than the solid [27].

1.2.2 Solid-State Bonding

Solid-phase bonding offers notable advantages, such as the absence of hot cracking, prevention of element segregation, and reduction of chemical and microstructural nonhomogeneities, without resolidifying the liquid metal. Additionally, it can reduce residual stress in the case of mass transport via atomic diffusion at elevated temperature, as in sintering.

Under ideal physical conditions, solid-state metallic bonding readily occurs when two atomically flat and clean metal surfaces come into intimate contact, because their cohesive atomic forces attract each other. Such a phenomenon occurs without necessarily applying pressure or raising temperatures. This is the origin of cold welding found at the nanoscale [28] and self-healing recently observed during fatigue testing [29]. However, in practical applications, metallic surfaces are seldom perfectly flat and are often covered by surface oxide layers and contaminant films (as illustrated in Figure 1.2). Moreover, microstructural and compositional irregularities can further complicate the joining process. These barriers against bond formation can be overcome by strain and/or heat through a number of mechanisms.

The first key mechanism is the creation of intimate contact via collapse of asperities [30]. When the temperature is increased, the yield strength decreases, making it possible for macroscopic mechanical loading to cause surface deformation with high local strains, ultimately resulting in contact of the two metal surfaces. Alternatively,

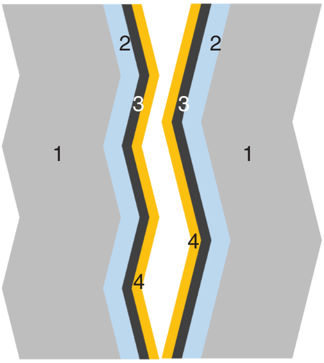

Figure 1.2 Different regions in two solid metal pieces close to contact: (1) base metal; (2) deformation region upon bonding; (3) oxide layer; (4) contaminant film.

such intimate contact can be created by creep and surface diffusion mechanisms at relatively low forces [31].

The second key mechanism is the removal of the surface oxides and contaminant films to allow atomic bonding [32]. This removal can be implemented by mechanically induced fracture (as seen in CSAM as an example), followed by material removal from the surface or dispersion into the matrix material. If the mechanical loading is inadequate but there is sufficient thermal energy, then the surface oxides may be removed in a reducing and/or low oxygen partial pressure atmosphere. This phenomenon is seen in sintering where bonding then occurs through atomic diffusion.

Another possible mechanism to facilitate solid-state bonding is the realignment of grain structures. The difference between crystallographic orientations on the two sides of the interface results in a series of high-angle grain boundaries, which may lead to inadequate joints. For example, in solid-state welding of Al, it is straightforward to form metallurgical bonds between (111) and (111) planes and between (110) and (110) planes, whereas bonding between (111) and (110) planes is difficult [33]. In terms of surface deformation, the dislocations created in the surface region followed by local recovery or recrystallization may help align the crystallographic planes across the interface.

1.3 Nonbeam-Based, Solid-State Metal Additive Manufacturing

The metal additive manufacturing technologies explored in this book are all based on solid-state bonding, i.e., without utilizing high-energy beams (e.g., lasers or electron beams) to melt the metals to create metallurgical bonding. Solid-state bonding mechanisms can further be divided into two subcategories.

The first is based on high-strain-rate deformation, where mechanical disruption of the oxide layer is followed by material bonding through severe plastic deformation. This can be induced by ultrasonic scrubbing, friction stirring, or supersonic impact of powder particles onto a substrate or a previous layer of the same material. UAM, AFSD, and CSAM processes fall under this category.

Alternatively, sintering-based solid-state additive manufacturing is characterized by consolidation of the 3D printed powder compact via uniform external heating up to a large fraction of melting temperature, i.e., sintering. Material bonding occurs by thermal reduction of the oxide layer on powder surfaces, allowing atomic diffusion between metal powder particles. BJAM and MEAM fall under this category. Sintering-based additive manufacturing techniques have the advantage of leveraging the mature knowledgebase on powder metallurgy and sintering technology.

1.3.1 Deformation-Based Metal Additive Manufacturing

Deformation-based metal additive manufacturing involves the application of shear and pressure to create metallurgical bonds between the newly deposited material and base material. CSAM, AFSD, and UAM are notable examples.

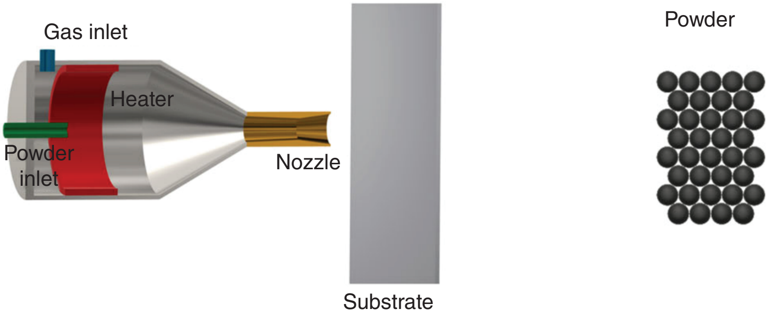

Figure 1.3 Illustration of the cold spray process, which uses powder as feedstock. Source: Yu and Mishra [34]/Taylor & Francis.

As shown in Figure 1.3, in cold spray, particles undergo acceleration to achieve supersonic velocities. This acceleration is achieved through the expansion of a gas that is both pressurized and heated, which takes place across a specialized convergent/divergent nozzle (i.e., a De Laval nozzle [35]). Following this acceleration, the microparticles experience collision with the base material, leading to the creation of a metallurgical bond. This collision-induced interaction leverages *local* deformation, and the basic microstructure of cold sprayed metals is bimodal in nature. Most cold sprayed metals have prior particle centers surrounded by the boundaries between prior particles; the contact regions where one prior particle collides with another display a thoroughly modified microstructure. Cold spray is widely used for corrosion and wear protection coatings, and it has been recently showcased for additive manufacturing purposes.

As shown in Figure 1.4, AFSD is characterized by a global deformation, where all the material voxels in the feedstock undergo severe plastic deformation at elevated temperatures [36]. This typically leads to significant microstructural changes as a result of dynamic recrystallization, characterized by the presence of

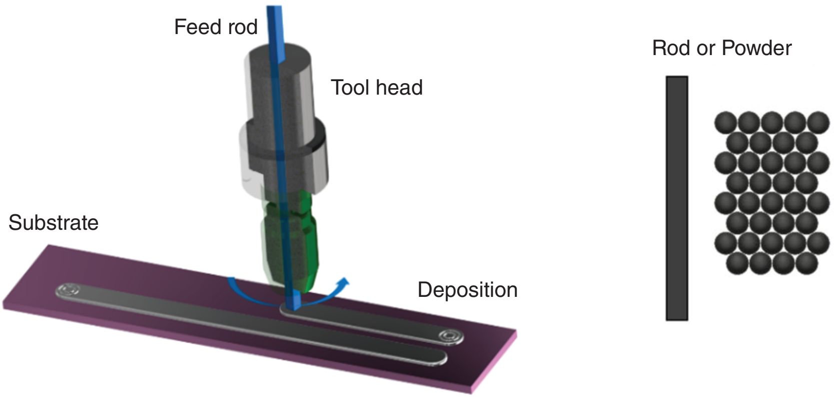

Figure 1.4 Illustration of additive friction stir deposition, which uses solid rod or powder as feedstock. Source: Yu and Mishra [34]/Taylor & Francis.

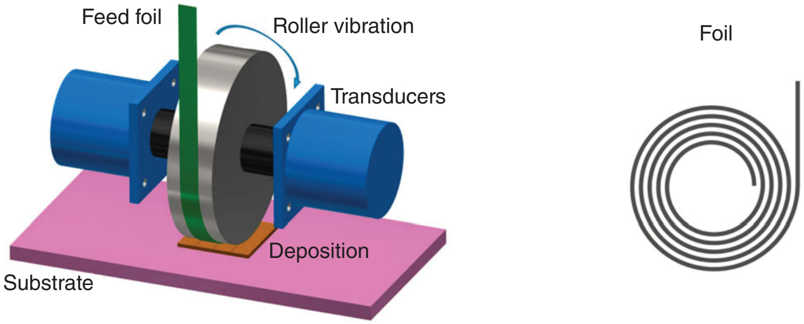

Figure 1.5 Illustration of ultrasonic additive manufacturing, which uses metal foil as feedstock. Source: Yu and Mishra [34]/Taylor & Francis.

fine, equiaxed grain structures. Moreover, the surface layers of the substrate or base material coplastically deform, and are mixed with the feed material, resulting in strong interfacial bonding. Thanks to extensive material flow, AFSD can lead to fully dense material in the as-printed state. Viewed as a forging-based additive process, the resulting mechanical properties can meet the forging standard. It has found applications in structural repair, selective area cladding, material recycling and upcycling, as well as manufacturing under austere conditions. The primary constraint is from its near-net-shaping nature, which requires removing material from the track edges through machining.

As shown in Figure 1.5, UAM only involves local deformation close to the interface, while the bulk of the feedstock (in the form of metal foil) remains at a low temperature without notable microstructural changes [37]. The localized and low-heat nature ensures minimal distortion and preserves the integrity of the original structure, making it suitable for various applications such as electrification, thermal management, and embedded electronics. The capability of bonding dissimilar metals and creating complex geometries further enhances its usage in diverse industries. However, the main limitation of UAM lies in its hybrid nature, which necessitates the use of CNC machining to achieve specific geometric features. Consequently, this hinders its application in scenarios like onsite repair and local remanufacturing.

To compare among these deformation-based additive processes, CSAM and UAM are relatively low-temperature processes involving local deformation, whereas AFSD features global plastic deformation at elevated temperatures. Both CSAM and AFSD are free forming processes that allow for location-specific deposition and repair, whereas UAM is a hybrid process leveraging both ultrasonic consolidation and CNC machining.

1.3.2 Sintering-Based Metal Additive Manufacturing

Sintering-based metal additive manufacturing involves an indirect method where a metal–polymer composite is initially crafted. This composite then goes through a series of postprocessing steps to eliminate binders or polymers, ultimately densifying the printed components through sintering (or hot isostatic pressing).

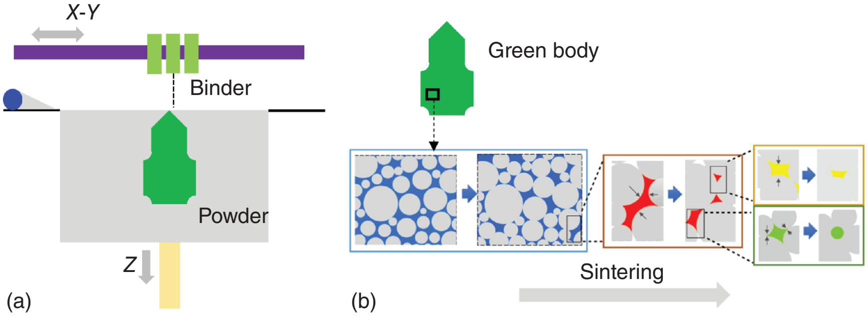

Figure 1.6 Illustration of (a) binder jetting and (b) pore evolution during post-processing.

One illustrative example within this realm is binder jetting, a process in which binders are precisely placed to glue metal powders together, resulting in a preliminary structure called a "green body," comprised of both metals and binders [38]. Then, the binders are removed at elevated temperatures, followed by sintering to achieve full density. The printing and postprocessing details are illustrated in Figure 1.6. It is also possible to print metals by utilizing typical polymer-based printing techniques such as material extrusion (or FDM), material jetting, and stereolithography. This is achieved by integrating metallic micro or nanoparticles with polymers. Following the printing process, a hybrid metal–polymer composite is generated. The subsequent step involves the selective removal of polymers, often through a process like burnout, followed by sintering of the metal component.

Sintering-based approaches in additive manufacturing present notable advantages, including lower energy consumption and the capability to fabricate intricate structures using multiple materials. Nevertheless, certain challenges persist, such as effectively managing shrinkage during the sintering process and ensuring a consistent distribution of density. These challenges continue to be subjects of ongoing research and development.

1.4 Additive Manufacturing Categorization Based on the Relationship Between Shape Forming and Consolidation

Another useful way of categorizing the additive manufacturing methods to understand the capabilities and resulting properties is the relative occurrence of building and consolidation stages described below:

(1) *Techniques where building and consolidation are* ***coupled***: These methods achieve layer bonding simultaneously as geometry is being built. Bonding can be achieved by using high-energy power to heat the feedstock until it melts and bonds or just enough to cause bonding through severe mechanical deformation. The heat source can be a laser beam as in SLM or DED, an electron beam as in EBM. The methods that fall under this category and rely on bonding through severe mechanical deformation are CSAM, UAM, and AFSD. Although the

Table 1.1 A summary of processing details, bonding mechanisms, resulting microstructures, and common examples of processed materials of the solid-state additive manufacturing methods covered in this book. An extensive comparison of the methods is discussed in [25].

Class	Method	Heating mechanism and maximum temperature	Bonding mechanism	Microstructure alteration and homogeneity	Processible materials	Common examples
Sinter-based AM	BJAM	Uniform - external heating >0.75 Tm	Atomic diffusion (generally following oxide reduction)	Minimal/Grain coarsening Homogeneous, equiaxed in all directions (except for some cases, see the text)	Any powdered material, including ceramics. Hard and brittle materials can be processed.	17-4PH, 316L, 304SS, Ti6Al4V, Inconel 625 and 718, Cu, Al_2O_3, Zr_2O_3, WC-Co
	MEAM	Uniform – external heating >0.75 Tm	Atomic diffusion (generally following oxide reduction)	Minimal/Grain coarsening Homogeneous, equiaxed in all directions (except for some cases, see the text)	Any powdered material, including ceramics Hard and brittle materials can be processed	17-4PH, 316L, H13, A2, D2 tool steels, Inconel 625, Cu, WC-Co
Deformation-AM	UAM	Local - interfacial frictional heating 0.2–0.5 Tm	Atomic diffusion; interface coalescence under pressure and temperature, assisted by high-strain-rate severe plastic deformation	Dynamic recrystallization, grain refinement and texture Nonhomogeneous, gradient from refined equiaxed grains at the interface to elongated grains with rolling texture of the foil	Mostly soft and ductile metals and alloys	Al alloys, Cu alloys, low carbon steels
	CSAM	Local – adiabatic Unknown (typically <Tm)	Severe plastic deformation	Adiabatic shear and dynamic recrystallization Grain refinement Fine grains at the particle interfaces	Mostly ductile metals and alloys that do not shutter or melt at supersonic impact conditions before exhibiting severe plastic deformation	Cu, Al, Mg Inconel 717, 625, Ti, Ti6Al4V, Bronze
	AFSD	Local - adiabatic 0.6–0.9 Tm	Severe plastic deformation	Dynamic recrystallization Grain refinement Equiaxed, fine, relatively random in all directions	Low temperature materials; more challenging for high temperature materials due to tooling	Various Al alloys (2xxx, 5xxx, 6xxx, 7xxx), Mg alloys, Cu, Ti6Al4V

Source: Adapted from [25].

physics behind these techniques are very different, the common characteristic of the methods in this category is that the *microstructure forms during building the geometry*. As the microstructure forms during printing in all these methods, the methods that involve high-energy beam melting suffer from anisotropic solidification microstructure, residual stress due to large thermal gradients, as well as the formation of brittle nonequilibrium phases due to rapid cooling, while CSAM, UAM, and AFSD generally result in fine microstructure and low residual stress.

(2) *Techniques where building and consolidation are* ***decoupled****:* This category involves the additive manufacturing methods that are based on powder metallurgy and sintering. These methods typically first produce an oversized geometry of the desired part by "gluing" together metal powder particles into a free-form 3D preform using polymeric binders, followed by a step that cleanly removes the organic binders (generally referred to as debinding), which is followed by the final consolidation of the part through sintering. BJAM and MEAM are among these methods. Although the layer-forming principle to build an oversized "green" geometry are different, the common characteristic of the methods in this category is that *the microstructure formation is independent of the geometry-building stage*.

Understanding the utilized bonding mechanisms and the relationship between shape forming and consolidation in various additive manufacturing techniques provides the necessary perspective to view these techniques in a comparative sense. Table 1.1 summarizes the processing details, bonding mechanisms, resulting microstructures, and common examples of processed materials of the solid-state additive manufacturing methods covered in this book. An extensive comparison of the methods is discussed in [25].

1.5 Organization of the Book

The book is organized into 17 chapters, each dedicated to exploring different aspects of solid-state metal additive manufacturing. With this chapter serving as the introduction, the rest of the chapters progress through the following topics:

Chapters 2–5: Cold spray additive manufacturing. Chapter 2 focuses on the conditions and mechanisms of impact bonding from a physics and materials perspective. Chapter 3 describes the microstructures in feedstock powders and their evolution during and after cold spray deposition. Chapter 4 provides an overview of the basic mechanical characteristics of cold spray deposits, including the interfacial adhesion properties and cohesion strength under both static and cyclic loading. Chapter 5 focuses on the current and potential applications of cold spray for various material systems, including surface enhancement, additive manufacturing, and surface restoration.

Chapters 6–9: Additive friction stir deposition. Chapter 6 focuses on the process fundamentals underlying AFSD, including temperature, force, and torque evolution, as well as material flow basics. Chapter 7 describes the dynamic microstructure evolution during AFSD of metals and metal matrix composites, highlighting various dynamic recrystallization mechanisms. Chapter 8 summarizes the mechanical behavior of various material systems in the as-printed state and after heat treatment. Chapter 9 discusses the niche applications enabled by AFSD, such as large-scale metal additive manufacturing, structural repair, cladding, as well as recycling and upcycling.

Chapters 10–12: Ultrasonic additive manufacturing. Chapter 10 overviews key bonding phenomena in ultrasonic consolidation, including oxide breakdown, asperity deformation, frictional heating, microstructural evolution around the weld interface, and interdiffusion during dissimilar metal consolidation. Chapter 11 presents an overview of the typical microstructural analyses, mechanical characterization methods, and hardness measurements for characterizing parts manufactured using UAM through case studies on Al and steel builds. Chapter 12 summarizes key industrial applications offered by UAM, including electrification, thermal management, and embedded electronics.

Chapters 13–16: Sintering-based metal additive manufacturing. Chapter 13 delves into the principles of solid-state sintering in metal additive manufacturing. Chapter 14 describes the fundamental aspects of material extrusion with specific attention to the hierarchy of printed objects, including the various length scales of objects fabricated. Chapter 15 provides an overview of binder jetting-based metal printing, including the feedstock, printing phase, and postprocessing treatment. Chapter 16 focuses on specific applications of printing magnetic materials using binder jetting.

Chapters 17: Future perspectives. The last chapter discusses future directions of solid-state metal additive manufacturing, such as enhanced understanding of process fundamentals, material innovation, and incorporation of artificial intelligence.

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