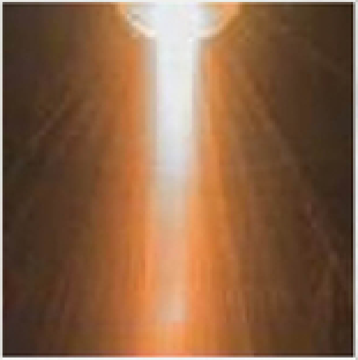

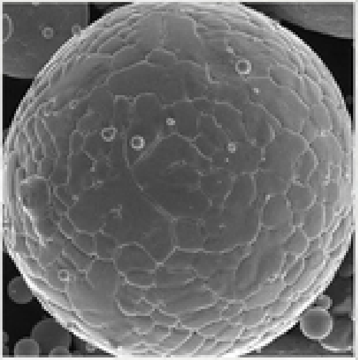

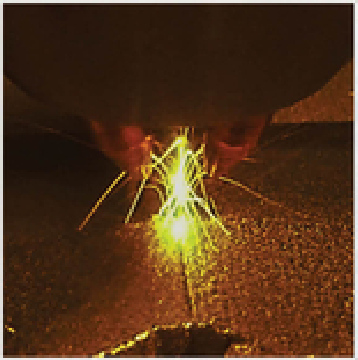

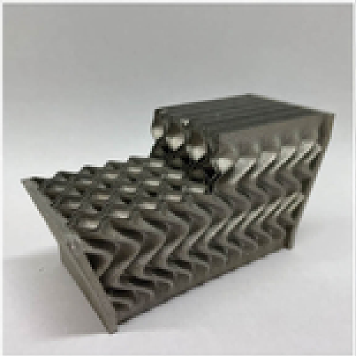

Metallic Powders for Additive Manufacturing

Science and Applications

Enrique J. Lavernia
Kaka Ma
Julie M. Schoenung
James F. Shackelford
Baolong Zheng

WILEY

On a Tree Fallen Across The Road

The tree the tempest with a crash of wood
Throws down in front of us is not to bar
Our passage to our journey's end for good
But just to ask us who we think we are
Robert Frost, American Poet, 1874–1963

Metallic Powders for Additive Manufacturing

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Science and Applications

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Contents

About the Authors

Dr. Enrique J. Lavernia, currently holds the title of Professor and M. Katherine Banks Chair, in the Departments of Materials Science and Engineering and Mechanical Engineering at Texas A&M University. Prior to that, he was a Distinguished Professor in the Department of Materials Science and Engineering in the Samueli School of Engineering (2015–2023) and the Provost and Executive Vice Chancellor for the University of California, Irvine from 2015–2020. Dr. Lavernia was previously engineering dean (2002–2008 and 2010–2015) at UC Davis and a Distinguished Professor of Chemical Engineering and Materials Science. He also served as UC Davis' provost and executive vice chancellor (2008–2010).

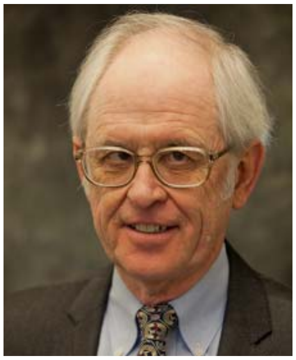
In 2022, Prof. Lavernia was recognized with an *R&D 100 Award* for his work with Dr. Todd Monson (Sandia National Laboratories, NM, USA) on Iron Nitride Soft Magnetics. Also in 2022, Dr. Lavernia was recognized with ASM International, *Albert Sauveur Achievement Award* "for *sustained and pioneering studies on the fundamental mechanisms that govern the interrelationship between processing, microstructure and mechanical behavior of structural materials."* He was elected as a Foreign Member of the Chinese Academy of Engineering in 2020. He also received the Acta Materialia Gold Medal in 2020. In 2019, Dr. Lavernia was awarded a *Doctor of Science in Technology, honoris causa,* by Aalto University, Helsinki, Finland. In 2018, he received the Distinguished Engineering Educator Award from the National Engineers' Council, and in 2017, he became a member of the National Academy of Inventors. Dr. Lavernia was elected to become a Fellow of the National Academy of Inventors in November 2016. Also in 2016, he received the Alexander von Humboldt Foundation Research Award as well as the Leadership Award from the TMS Society. In 2015, he was inducted into the Hispanic Hall of Fame by the HEENAC Great Minds in STEM. In 2014, he was awarded the TMS Fellows Award Class of 2014 by the Minerals, Metals and Materials Society. Elected to the National Academy of Engineering in 2013, Dr. Lavernia is also a fellow of the Minerals, Metals and Materials Society, the Materials Research Society, the American Society of Mechanical Engineers, the American Association for the Advancement of Science, and ASM International. He is the recipient of the 2013 Edward DeMille Campbell Memorial Lectureship and the 2013 ASM International Gold Medal Award. Named Presidential Young Investigator by the National Science Foundation, Dr. Lavernia also received a Young Investigator Award from the Office of Naval Research. In 2011, he received the Hispanic Engineer National Achievement Award and the Society for the Advancement of Chicanos and Native Americans in Science Distinguished Scientist Award.

Dr. Lavernia has published over 670 journal papers, 231 conference papers, 1 book, 11 edited books/journals, and 21 book chapters and has been awarded 11 patents on topics ranging from nano-materials to aluminum alloys. His research interests include the synthesis and behavior of nanostructured, high entropy, and multi-scale materials with particular emphasis on processing fundamentals and physical behavior; high temperature-high pressure atomization processes; and additive manufacturing. He earned his BSc from Brown University in 1982 and his MSc and PhD degrees in 1984 and 1986, respectively, from the Massachusetts Institute of Technology.

Dr. Kaka Ma is an Associate Professor in the Department of Mechanical Engineering and the School of Materials Science and Engineering at Colorado State University (CSU). She earned her B.S. degree in materials physics from the University of Science and Technology of China in June 2006, and then PhD in materials science and engineering from the University of California (UC), Davis in December 2010. Following several years of postdoctoral research and some part-time instructor experiences at UC Davis and UC Irvine, she joined CSU as a tenure-track Assistant Professor in August 2016. Ma's research interests sit at the interface of materials science, mechanical engineering, and sustainability. Her research is focused on powder metallurgy for both metals and ceramics, with the overarching goal of discovering new processing-structure-properties correlation to sustainably develop materials for next-generation structural, electronic, and energy components. Her research group mainly utilizes spark plasma sintering and laser-directed energy deposition to develop functionally graded materials, thermionic materials, and structural materials and investigate the sustainability issues associated with these powder technologies. She has published more than 50 peer-reviewed journal papers, given about 20 invited talks, and authored more than 70 presentations at technical conferences, workshops, and at other universities. She is a member of the Minerals, Metals & Materials Society (TMS), Material Research Society (MRS), and America Makes. Ma is the founding editor and Editor-in-chief of Results in Materials. She has also been serving on the reviewer/editorial board for Materials Science & Engineering A, Journal of the American Ceramics Society, Journal of Materials Science, Additive Manufacturing, and so forth.

Professor Julie M. Schoenung currently holds the title of Professor and Wofford Cain Chair III in the Departments of Materials Science and Engineering and Mechanical Engineering at Texas A&M University. She is also the Founding Co-Director of the Lincoln Dynamic Foundation World Institute for Sustainable Development of Materials (WISDOM). Prior to joining Texas A&M, Professor Schoenung served as the Founding Department Chair in the Department of Materials Science and Engineering at the University of California, Irvine (UCI) and held the title of Distinguished Professor. She also held the Daniel G. Aldrich, Jr. endowed chair position at UCI. Prior to her positions at UCI, Professor Schoenung held faculty appointments UC Davis and at Cal Poly Pomona (California State Polytechnic University, Pomona).

Professor Schoenung is a member of the National Academy of Engineering (NAE), and a Fellow of the American Association for the Advancement of Science (AAAS), the National Academy of Inventors (NAI), the Minerals, Metals and Materials Society (TMS), the Materials Research Society (MRS), ASM International, the American Ceramic Society, and the Alpha Sigma Mu Honor Society. Professor Schoenung received her PhD and MS in materials engineering from the Massachusetts Institute of Technology, and her BS in ceramic engineering from the University of Illinois, Urbana-Champaign. Professor Schoenung conducts research into structure-processing-property mechanistic relationships in a variety of materials systems. Her current research focus is on high entropy ceramics and additive manufacturing of ceramics, cermets, composites, and metals, including the application of alternative feedstock materials generated from waste products. Professor Schoenung is also a pioneer in the field of sustainable development of materials, with many years of experience studying the materials-selection process in a variety of applications. She conducts research into the analysis of factors that guide the materials-selection decision-making process, such as economics, environmental impact and toxicity, cost-performance trade-offs, policy, and sustainability standards.



James F. Shackelford has BS and MS degrees in Ceramic Engineering from the University of Washington and a PhD in Materials Science and Engineering from the University of California, Berkeley. Following a postdoctoral fellowship at McMaster University in Canada, he joined the University of California, Davis, where he is currently a Distinguished Professor Emeritus in the Department of Materials Science and Engineering and is a Visiting Professor Emeritus at UC Irvine. For many years, he served as the Associate Dean for Undergraduate Studies in the College of Engineering at UC Davis and later as the Director of the University Honors Program that serves students from a wide spectrum of majors. He teaches and conducts research in the structural characterization and processing of materials. His current focus in teaching is doing so through online technologies. A member of the American Ceramic Society and ASM International, he was named a Fellow of the American Ceramic Society in 1992, was named a Fellow of ASM International in 2011, and received the Outstanding Educator Award of the American Ceramic Society in 1996 and the Albert Easton White Distinguished Teacher Award from ASM International in 2019. In 2016, Professor Shackelford received the Inaugural Award for Outstanding Contributions to Materials Education at the North American Materials Education Symposium (NAMES) held at the University of California, Berkeley. He has published over 150 archived papers and books including *Introduction to Materials Science for Engineers* now in its 9th Edition and which has been translated into Chinese, German, Italian, Japanese, Korean, Portuguese, and Spanish. He is also the coauthor of the *CRC Materials Science and Engineering Handbook* now in its 4th Edition and *The Glass of Wine* covering the intersection of the glass and wine industries published by The American Ceramic Society and Wiley.

Dr. Baolong Zheng holds a Bachelor of Science degree (1987) and a Master of Science degree (1989) in Metallurgy and Materials Engineering from the University of Science and Technology Beijing (USTB) in China. He also obtained a PhD in Materials Science and Engineering from the University of California (UC) Davis in the USA in 2006. Following the completion of his PhD, Dr. Zheng worked as a Postdoctoral Researcher and Research Scientist at UC Davis (2006–2015) and UC Irvine (2016–2024), where he specialized in research on gas atomization (GA), additive manufacturing (AM) deposition, and field assisted sintering technologies (FAST). He worked on developing Al-, Ti-, Ni-, Mg-, and Fe-based alloys and metal matrix composites (MMCs) using these technologies, as well as Al-Ni metallic foam materials. He has expertise in the synthesis and characterization of non-equilibrium nanostructured and amorphous Mg-, Fe-, and Al-based alloys, high entropy alloys, soft magnetic materials, and MMCs, achieved through various powder metallurgy and thermo-mechanical processing techniques including GA, high-energy milling/cryomilling, AM, SPS, CIP/HIP, extrusion, ECAP, HPT, and rolling.

Dr. Zheng has an extensive background in academia and research. He was an R&D Engineer (1990–1993) at the National Engineering Research Center for Adv. Rolling Technology of China (NERCAR), an Assistant Professor (1993–1996) and Associate Professor (1997–2000) at USTB, and a Research Assistant (2000–2001) at UC Berkeley.

Dr. Zheng has published over 90 journal papers, more than 100 conference presentations, and 8 books or chapters, showcasing his contributions to the field of metallurgy and materials engineering.

Preface

Motivation

In recent years, additive manufacturing (AM) has evolved as an important manufacturing approach that has the potential to revolutionize the fabrication of both advanced and conventional materials by simplifying the number of process steps that are required to attain a final product, particularly with complex three-dimensional geometries. This is consistent with the data shown in Figure 1, which summarizes the statistical data of articles on the topic of additive manufacturing published up to 2019 as well as the number of additive manufacturing papers under specific material term searches.

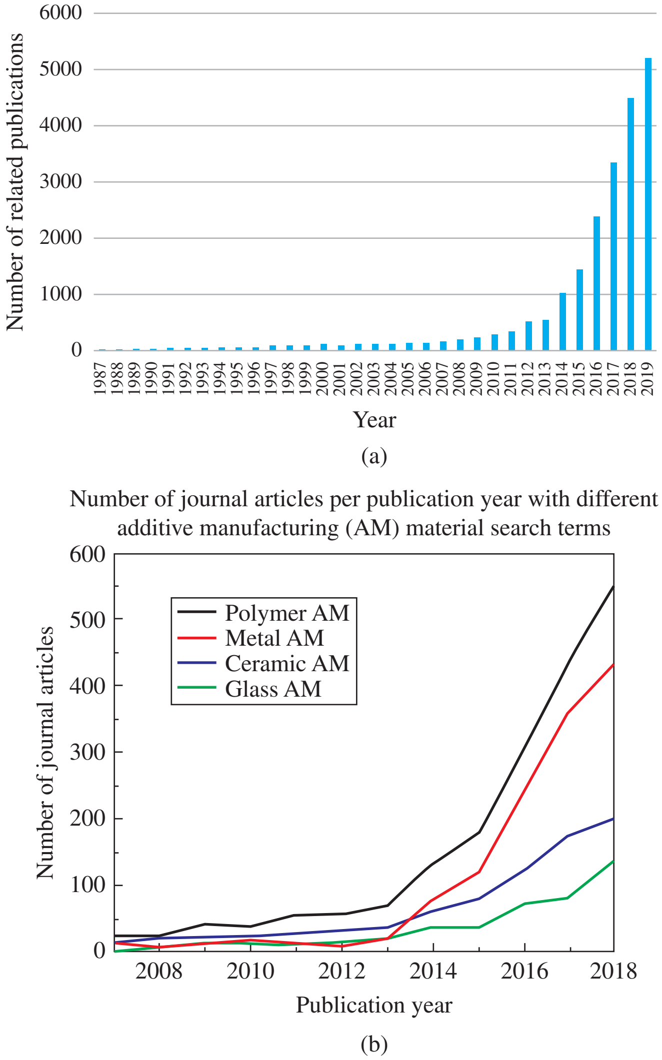
It is evident from a review of the published literature as well as from extensive industrial interests in additive manufacturing that many existing metallic additive manufacturing technologies require powder as the raw input material, and mostly rely on atomized metal powders as the source material. The quality of starting powder, such as chemical composition, particle size, and morphology, is critical to successful attempts to produce functional additive manufacturing components. It is also evident that although atomization has existed for several hundred years, the complex interrelationships that exist between the characteristics of the metal powders and the requirements of additive manufacturing remain largely unexplored. Moreover, it is also evident based on a large body of literature that perhaps one of the most critical elements that is hindering progress in additive manufacturing is in fact a lack of knowledge of the precise role that metal powders play in determining both the processing as well as the final performance of additively manufactured parts.

The motivation for this book is to introduce the reader to both the science and technology of atomized metal powders and how these relate to the process of additive manufacturing. The book seeks to set a foundation for the underlying science that governs the formation and microstructure of atomized metallic droplets. This information is then correlated with the behavior of metallic powders during additive manufacturing. We seek to establish the fundamental relationships that exist among the chemistry, microstructure, and morphology of atomized metallic powders and their behavior during additive manufacturing.

It was an important goal of the authors to deliver a book that is comprehensive in its coverage of all topics related to the atomization of metal powders and additive manufacturing. Concepts are introduced at a fundamental level, placing particular emphasis on information that relates to practical engineering problems. As such, the book is useful to the novice but also serves as a reference book for those who are active in the practice of metal powder atomization and/or additive manufacturing. We hope that the book will also play a role in education, and as such, we envision this book to be useful as a reference book in graduate or advanced undergraduate courses, for example.

Organization

In this book, we begin with a description of the fundamentals of powder atomization to familiarize the reader with the mechanisms that govern microstructure evolution in atomized metal powders. We describe the variety of processes that currently exist for the atomization of metal powders. We then establish the relationships that exist between the characteristics of atomized powders and the performance requirements of additively manufactured parts. We also discuss alternative feedstock materials for metal additive manufacturing other than atomized powder, such as powders produced from ball milling of machining chips, and how these alternative feedstock materials affect



(a)

(b)

Figure 1 (a) Statistical data of articles on the topic of additive manufacturing published in 2019, based on the database of Web of Science Core Collection in July 2020 [1], and (b) number of additive manufacturing papers under specific material term searches [2].

the choices of additive manufacturing processing windows (parameters) and the microstructure and properties of the final additive manufacturing parts. We finish with a perspective on the potential influence of metal powder atomization and additive manufacturing on environmental impact and economic viability, which is less commonly addressed in the current literature, and, we provide a brief outlook on the short-term needs and long-term future directions of metal powders for additive manufacturing.

In Part I, we begin with an introduction to the process of atomization describing the various methods that exist to generate metallic droplets. We proceed to describe the various theories that exist to describe the formation of droplets, the physics that govern their morphology, and their ultimate overall microstructure evolution. We discuss the parameters that exercise some degree of control over atomization paying, particular attention to ones that directly affect the particle size distribution and how these are related to the various processing variables. We discuss the various models that exist to describe the mechanisms that govern atomization. The book then addresses the heat transfer and solidification of droplets, paying particular attention to the critical thermal and solidification conditions that govern the evolution of microstructure.

In Part II, we introduce the various processes that are used for additive manufacturing and the relationship between metal powder characteristics and additive manufacturing processing, and ultimately part quality. This section of the book begins with an overview of the various techniques that are used to produce additively manufactured components. The next chapter covers powder-laser-molten-pool interactions, followed by the influence of powder production methods and chemistry on additive manufacturing. We then discuss the influence of powder on microstructure evolution, defect formation, and residual stress, respectively, and finally present a discussion on the influence of powder on the physical and chemical behavior of additively manufactured parts. Our final two chapters describe societal issues (such as economic viability and sustainability) followed by perspectives on future directions and challenges.

January 2024

Enrique J. Lavernia
Kaka Ma
Julie M. Schoenung
James F. Shackelford
Baolong Zheng

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Enrique J. Lavernia

I sincerely thank my family, whose steadfast support and boundless affection have been my pillars, particularly in challenging circumstances. I am deeply thankful to my spouse and soulmate, Julie Schoenung, whose enduring patience, love, and encouragement have been instrumental in my life. My amazing children, Alejandro Carlos and Laura Kathryn, who consistently bring me happiness, pride, and unwavering backing. The spirit and love of my brother, Carlos J. Lavernia, is a remarkable guardian over me and our family.

I also thank my wonderful MSE colleagues and dedicated staff for their care, integrity, and hard work. My long-time friend and colleague, Jeff Lefkoff, has always been there for me on our regular beach walks and for lending a listening ear. My countless friends and colleagues locally, nationally, and globally, including Diran Apelian, Michael Stamos, Horst Hahn, and many others whose friendship and care have sustained me.

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Kaka Ma

I would like to start by thanking Dr. Enrique Lavernia for inviting me to this exciting opportunity to discuss and share experiences, opinions, and visions of the impactful and rapidly expanding field of additive manufacturing, focusing on the topic of metallic powders. I cannot express enough gratitude to my former PhD advisor, Dr. Julie M. Schoenung, who not only trained me with professional attributes and encouraged me to my current career stage but also became a good friend, always lending her ears and sharing her wisdom when I face challenges in work or life. I am deeply grateful to this awesome team of coauthors, Enrique, Julie, Jim, and Baolong, for the fruitful discussions along the way and their understanding and patience when things slow down.

I am always grateful to my family for the constant love and support. I appreciate my husband, Dr. Xiaochuan Tang, for his understanding and support of my commitment to writing this book in addition to my regular faculty working loads. He not only took care of extra household chores, but also provided valuable insights and suggestions, given his background of applied physics and his expertise in computational materials science when I was writing this book. My kids, Erika Tang and Ethan Tang, always cheer me up with joy and pride, as well as endless childish yet inspiring questions. I also appreciate the resources and support provided by Colorado State University that allow me to advance my research in the field of advanced manufacturing. I am thankful to my colleagues at CSU, who have supported me in my career path in many ways.

Julie M. Schoenung

I wish to thank my coauthors for their hard work, collegiality, and patience while writing this book together. I've learned a great deal from them, both technically and professionally. We have worked together very well as a team, with the persistent encouragement of each other and especially our team leader, Dr. Enrique J. Lavernia. I also wish to acknowledge the significant contributions of Dr. Xin Wang. Her efforts expanded the scope of the book beyond what was originally planned. I thank Dr. Jim Shackelford for being the first person to ever invite me to contribute a chapter to a book. I thank Kaka Ma, Xin Wang, and more than twenty other PhD and master's students for keeping me inspired to learn new things and for giving me the opportunity to relish in their career growth and success. I thank Baolong Zheng, Yizhang Zhou, Darryl Mack, Alex Dupuy, Amy Ricks, and the MSE staff for constant technical and administrative support to keep my group and the department running while I spent time working on this book. Their loyalty is immeasurable. I thank my faculty colleagues and collaborators for always encouraging me to think outside the box, and to not be afraid to venture into new fields of research. Working at the intersection of disciplines has kept me motivated and has allowed me and my colleagues to have a greater impact and to hopefully move the needle, at least slightly. I wish to thank my family for their love and support throughout my life, my career, and while working on this book. To my husband, Enrique, and to our children, Alejandro and Laura, my most sincere gratitude for always believing in me and supporting me despite my frequent moments of doubt. To my parents, Alois and Rita Schoenung, for believing in the value of education, and investing in their daughters despite limited resources. To my sisters, Chris, Marji, Suzi, and Kathy, for letting me be the baby of the family, yet nurturing my independence, as well as my personal, spiritual, and intellectual growth. A special thank you to Suzi for forging the path into both engineering and graduate studies. Finally, to so many other role models, including the countless unnamed and unrecognized women scientists and engineers who opened the doors of opportunity for the rest of us to follow.

James F. Shackelford

I begin by acknowledging Enrique Lavernia for inviting me to join him and an excellent group of coauthors to cover this important and timely discussion of the rapidly emerging field of additive manufacturing of metals. My family has been more than "patient and understanding" during this and other writing projects. Penelope has been an occasional coauthor as well as family matriarch, master chef and sommelier. Our son Scott and his family, Megumi, Mia, and Toki are a constant source of joy and pride. I am also deeply grateful to colleagues at the University of California, Davis and the University of California, Irvine who continue to encourage and support my ongoing explorations in the endlessly fascinating material world.

Baolong Zheng

I would like to express my deepest gratitude and appreciation to my former PhD advisor, current mentor and boss, Professor Enrique J. Lavernia for his advice, guidance, inspiration, and support in helping me complete my dissertation, papers, and presentations, and various research projects. His erudition and insights, enthusiasm, and optimism provided me with an endless source of knowledge and energy. Thanking him for bringing me to work in these rich scientific content and vibrant fields of gas atomization and additive manufacturing (my dissertation: Synthesis and behavior of metallic glasses via gas atomization and laser deposition). At that time, Prof. Lavernia's group was one of earliest research labs working on directed energy deposition (DED) (laser engineering net shipping [LENS]) of additive manufacturing in the world. Special words of thanks also go to Dr. Yizhang Zhou, Darryl Mack and all the other colleagues. My very special thanks to my wife, Xiaoting, and my twin daughters, Penny and Annie, for their profound love, patience, understanding, and unconditional support throughout my life, studies, and work in the USA.

Part I

Atomization of Metallic Powder

1

Overview of Atomization Techniques

1.1 History of Metallic Powder and Atomization Techniques

1.1.1 Metal Powders

The high surface-to-volume ratio (i.e. volume per surface area) of a sphere renders it an ideal geometry for handling, pressing, forming, and/or reacting particles into a bulk form. It is hence not surprising that **metal powders**, in their most elementary form, emerged as useful "engineering" materials, even in ancient times. **Metal powders** can be produced using either chemical/**mechanical methods** or **fluid atomization**. Mechanical methods involve the physical breakdown of a large particle into a smaller one, whereas **chemical methods** typically involve a solid-state process in which a metal oxide is reduced into a metal. For example, the reduction of iron, also called sponge iron, occurs when iron ore is exposed to a reducing gas. Powders produced using chemical reduction methods are not widely used in **additive manufacturing (AM)** and hence are not covered in this chapter. There is some preliminary research on the use of powders produced by mechanical methods in AM, and these will be discussed in a subsequent chapter.

Powder metallurgy, as the practice of working with metal powders is widely known, has a rich history, from the Incas using powder techniques to work precious metals to ancient Egypt, Africa, and India (see Table 1.1). In fact, the use of elevated temperature metals can be traced back about 7 000 years, long before furnaces capable of reaching the temperature required for melting them. Hence, it has been suggested that objects made of iron about 5 000 years ago were likely fabricated using powder metals. The first application of a powder metal product was a bronze ball bearing, capable of self-lubrication and used for automotive applications in 1927 [1].

The Oxford dictionary defines the word ***atomize*** as to reduce something into atoms or into very small pieces. Clearly, based on this definition, one can hypothesize that the term atomization has been loosely applied to the disintegration of any bulk material into smaller components. One can envision the disintegration of water as it emerges from a nozzle or waterfall into droplets or similarly the disintegration of rock by mechanical means into very small pieces. Fluid atomization, however, is generally described as a process where a liquid metal is disrupted by a high-velocity fluid such as air, nitrogen, argon, helium, or water in some cases. The actual process of atomization occurs when there is a transfer of **kinetic energy** from the atomizing medium to the metal being disintegrated. There are different forces in action during atomization that depend on the fluid being used for the energy transfer. In the case of water, for example, it is typically the pressure of the medium that dictates the efficiency of the atomization process and thereby the resultant distribution of droplets that emerges during disintegration. In the case of **gas atomization (GA)**, however, it is typically found that the gas-to-metal ratio dominates the resulting distribution of droplets, and various mathematical relationships have been developed to capture this relationship. In the case of gases, for example, increases in pressure that exceed 0.1 MPa (this is the pressure at which a **sonic velocity** is reached) result in only very small increments in gas velocity. In comparison, to reach sonic velocity with a water jet, for example, a pressure of nearly 40 MPa is needed in the case of water, and velocity continues to increase as the square root of the pressure.

There are various methods that can be effectively used to produce metal powders from valuable metals and alloys such as **nickel**, **cobalt**, copper, titanium, aluminum, and stainless steel base alloys. However, GA is generally viewed as the method of choice due to its capacity for large production quantities, the ability to control chemistry, and the geometrical properties of the powder particles that can be produced. These characteristics render atomization as the preferred technique to manufacture powders for AM, although, as we will discuss in subsequent chapters, alternative methods for powder preparation are being explored.

Metallic Powders for Additive Manufacturing: Science and Applications, First Edition.
Enrique J. Lavernia, Kaka Ma, Julie M. Schoenung, James F. Shackelford, and Baolong Zheng.

Table 1.1 Major Historical Developments in Powder Metallurgy.

Date	Development	Origin
3000 BCE	"Sponge iron" for making tools	Egypt, Africa, India
1200 CE	Cementing platinum grains	South America (Incas)
1781	Fusible platinum-arsenic alloy	France, Germany
1790	Production of platinum-arsenic chemical vessels commercially	France
1822	Platinum powder formed into a solid ingot	France
1826	High-temperature sintering of platinum powder compacts on a commercial basis	Russia
1829	Wollaston method of producing compact platinum from platinum sponge (basis for the modern PM technique)	England
1830	Sintering compacts of various metals	Europe
1859	Platinum fusion process	
1870	Patent for bearing materials made from metal powders (the forerunner of self-lubricating bearings)	United States
1878–1900	Incandescent lamp filaments	United States
1915–1930	Cemented carbides	Germany
Early 1900s	Composite metals	United States
	Porous metals and metallic filters	United States
1920s	Self-lubricating bearings (used commercially)	United States
1940s	Iron powder technology	Europe
1950s and 1960s	Powder metallurgy wrought and dispersion-strengthened products, including powder forgings	United States
1970s	**Hot isostatic pressing**, PM tool steels, and superplastic superalloys	United States
1980s	Rapid solidification, powder injection molding technology, and binder-treated ferrous premixes	United States and Europe
1990s	Intermetallics, metal–matrix composites, spray forming, nanoscale powders, water-atomized pre-alloyed ferrous powders with **molybdenum** as the principal alloying element, and warm compaction	United States and United Kingdom
2000s	Warm-die compaction, additive manufacturing (3D printing) on a commercial basis	United States and Europe

Source: Samal and Newkirk [1] / ASM International.

1.1.2 Atomizer Designs

A critical aspect of atomization technology involves **atomizer design**. The atomizer is used to disintegrate the molten materials into a dispersion of droplets, which eventually solidify into powders, and therefore different designs result in various distributions of droplet (and hence powder) sizes. Since size distribution is an important variable that governs the solidification behavior of droplets, atomizer design directly influences the resultant microstructure of the powder, and hence the final properties of the consolidated material. Historically, a variety of atomizer designs have been developed to various degrees of success. There is, however, no general agreement among the scientific community as to the optimal atomizer design; more likely, the design used depends on the desired powder characteristics and the ultimate intended application of the powder. Moreover, and as will be addressed in a later chapter, optimal processing parameters and atomizer design are often material-specific (these can change even for slight compositional variations).