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Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.
Foreword

Whenever a new volume is considered for addition to the ASM Handbook series, great care and thought are taken to ensure the subject matter meets a demand from the market and that the leading technical experts are at the helm to develop the content. ASM International’s latest effort, ASM Handbook, Volume 24, Additive Manufacturing Processes, hits both marks. The list of contributors reads like a who’s who of the additive manufacturing world, and together they have created a comprehensive compendium of reference information on the growing topic of additive manufacturing. This handbook is a practical resource covering the processes used to additively manufacture polymers, ceramics, and metals, including direct-write methods.

ASM International is grateful for the work and dedication of volunteer editors, authors, and reviewers who devoted their time and expertise to develop a reference publication of the highest technical and editorial caliber. A special note of thanks is offered to the volume and division editors who put forth extraordinary efforts to keep this project focused and completed on schedule.

Dr. Zi-Kui Liu, FASM
President
ASM International

Ron Aderhold
Acting Managing Director
ASM International
Preface

For almost 100 years the ASM Handbook has captured the ongoing growth of applied knowledge covering the complete array of industrial materials and manufacturing processes. Within this archive, a major theme is the progressive development of materials having ever greater strength and heat resistance, primarily to meet performance objectives of transportation and defense applications. Unfortunately, the characteristics of such materials present challenges to the principal shaping processes of forming and material removal in reaching the complex shapes required. This, in turn, led to a parallel trend toward net shape to reduce or eliminate the negative aspects of material removal.

In more recent times, however, a completely different approach to shape making has evolved in which basic materials in liquid or particulate form, as well as filament or sheet form, are assembled point by point or layer by layer into the objective shape. Using the pinpoint accuracy of a laser, miniscule droplets from a printhead, or extrusion of material through a narrow nozzle, a variety of clever mechanisms have been devised to carry out these high-resolution building processes, now collectively known as additive manufacturing (AM), and frequently referred to as 3D printing. The current and rapidly expanding importance of AM merits its capture within this, ASM Handbook, Volume 24, Additive Manufacturing Processes. As a starting point, the first division presents an overview of the subject as well as deep insights into its historical development, authored by some of the key participants in that history as they trace the evolution of AM from its pre-computer roots to early commercialization of (largely) rapid prototyping machines, to modern serious tools for production of parts from all material classes.

A primary result of these newfound processes is the capability to produce shapes of greater complexity and with more refined geometric detail than can be obtained by conventional processes covered in previous ASM Handbook volumes. In fact, such capabilities enable designers and manufacturers to think beyond net shape and toward optimum shape – the placement of material only where it is needed to carry out the required transmission of stress, temperature, or electromagnetic fields. In addition, thermo-fluid management systems, such as heat exchangers and molding tools, can incorporate non-round and non-straight internal channels for enhanced efficiency. A further advantage of AM’s geometric flexibility is the combination of multiple parts into one component, eliminating assembly operations as well as individual part tooling and inventory. One highly publicized example involves the integration of some 20 parts into one fuel injection nozzle for aircraft turbine engines. To illustrate the advanced industrial development of AM, this component has been in mass production for more than a year at this writing.

Another exciting opportunity afforded by AM is modification of a material’s properties. The introduction of engineered porosity (i.e., printing material around void spaces) and lattice structures within the boundaries of the part effectively reduces its density, which is of great value in any transportation related application. The same approach can be used to spatially modify the localized density, strength, and thermal properties of a part, enabling functionally gradient materials to accommodate different needs in different locations of a part or component. In an advanced form, AM enables spatial variation of properties by building the parts with different materials point-to-point, or by varying process parameters to accomplish different microstructures within the same part.

This wide latitude in shape, structure, and compositional control has injected a spirit of excitement in the materials, design, and manufacturing communities. Materials science and engineering has a new field in which to apply the basic concepts of materials structure through advanced tools for material characterization. Likewise, designers now wander into a new world of possibilities opened by the seemingly limitless geometric flexibility of AM. Manufacturers can now consider a new array of development and production processes with potentially more efficient materials use, reduced time to market, and greater performance.

This Volume of the ASM Handbook series seeks to promote the excitement of AM by providing the latest knowledge in materials, processes, and applications. Following the history and introductory division, the complete suite of materials and processes for polymers and ceramics are detailed in the next two divisions. The fourth division describes the metal AM processes, but begins with in-depth description of the production and characterization of metal powders; such information has an outsized effect on success or failure of metal AM processes. The fifth division describes AM processing of a wide variety of materials, illustrating differences in characteristics of metal alloys produced by AM processes in contrast to conventional processes. The final division covers direct-write processes, taking advantage of AM processes to combine materials and devices for multifunctional engineering applications. Additional volumes are planned covering design and applications for additive manufacturing.

We wish to acknowledge the immense efforts by the article authors and division editors to bring this volume together. Considerable time is required to complete these assignments which, unfortunately, come at a time when the talents of the authors are in high demand within this rapidly expanding and dynamic industry as it evolves continuously to new levels of achievement.

Howard Kuhn, FASM
David L. Bourell, FASM
William Frazier, FASM
Mohsen Seifi
Contributors

Magnus Ahlfors
Quintus Technologies

Arulselvan Arumugham Akhilan
University of Louisville

Vince Anewenter
Milwaukee School of Engineering

Sundar V. Atre
University of Louisville

John Barnes
The Barnes Group Advisors

Saurabh Basu
Pennsylvania State University

Joseph J. Beaman
University of Texas at Austin

Allison Beese
Pennsylvania State University

Lindsey B. Bezek
Virginia Polytechnic Institute and State University

David L. Bourrell
University of Texas at Austin

Carelyn E. Campbell
National Institute of Standards and Technology

Prem Chahal
Fraunhofer Center for Coatings and Diamond Technologies

Kristin M. Charipar
U.S. Naval Research Laboratory

Yong Chen
University of Southern California

Zhangwei Chen
Shenzhen University

Kenneth Church
nScrypt, Inc.

Brett P. Conner
Youngstown State University

Frank Cooper
Birmingham City University School of Jewellery

Jose Coronel
The University of Texas at El Paso

Chase Cox
MELD Manufacturing Corp.

Corson Cramer
Oak Ridge National Laboratory

Carl Dekker
MET-L-FLO Inc.

E.R. Denlinger
Autodesk Inc.

Phill Dickens
University of Nottingham

Amy Elliott
Oak Ridge National Laboratory

Ravi K. Enneti
Global Tungsten and Powders Corp.

David Espalin
The University of Texas at El Paso

David Fletcher
Cooksongold

Diana Ganzina
SLAC National Accelerator Laboratory

Jerard V. Gordon
Carnegie Mellon University

Robert J. Griffiths
Virginia Tech

Gautam Gupta
University of Louisville

John Halloran
University of Michigan

Adam Hehr
Fabrisonic LLC

Neil Hopkinson
XAAR3D

Timothy Horn
North Carolina State University

Wayne Hung
Texas A&M University

Harish Irrinkin
University of Louisville

Jay Keist
Pennsylvania State University

Dominic Kelly
The University of Texas at El Paso

Shawn Kelly
Oerlikon AM

Heinrich Kestler
Plansee SE

Samyeon Kim
Singapore University of Technology and Design

Edward Kinzel
University of Notre Dame

M.M. Kirka
Oak Ridge National Laboratory

Howard Kuhn
University of Pittsburgh

David K. Leigh
EOS North America

Ming C. Leu
University of Southern California

Xiangjia Li
University of Southern California

Guangyi Ma
Dalian University of Technology

Eric MacDonald
Youngstown State University

John Martin
Youngstown State University

Richard P. Martukanitz
University of Virginia and Commonwealth Center for Advanced Manufacturing

Eric Maynard
Jenike & Johanson

Brian McTiernan
Powdered Metals Consulting LLC

Nicholas Meisel
Pennsylvania State University

P. Michaleris
Autodesk Inc.

Amir Mostafaei
Carnegie Mellon University

Peevush Nandwana
Oak Ridge National Laboratory

Abdalla R. Nassar
Pennsylvania State University
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Retired

Martin Jones  
Ford Motor Company

Brad Lindner  
Element Materials Technology

Dana Medlin  
EAG Laboratories, Inc.

Roger Narayan  
UNC-NCsu Dept of Biomed Eng

Valery Rudnev  
Inductoheat Incorporated

Muthukumarasamy Sadayappan  
Natural Resources Canada

Satyam Suraj Sahay  
John Deere Technology Center India

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Material Processing Technology LLC

John M. Tartaglia  
Element Materials Technology Wixom Inc.

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Policy on Units of Measure

By a resolution of its Board of Trustees, ASM International has adopted the practice of publishing data in both metric and customary U.S. units of measure. In preparing this Handbook, the editors have attempted to present data in metric units based primarily on Système International d’Unités (SI), with secondary mention of the corresponding values in customary U.S. units. The decision to use SI as the primary system of units was based on the aforementioned resolution of the Board of Trustees and the widespread use of metric units throughout the world.

For the most part, numerical engineering data in the text and in tables are presented in SI-based units with the customary U.S. equivalents in parentheses (text) or adjoining columns (tables). For example, pressure, stress, and strength are shown both in SI units, which are pascals (Pa) with a suitable prefix, and in customary U.S. units, which are pounds per square inch (psi). To save space, large values of psi have been converted to kips per square inch (ksi), where 1 ksi = 1000 psi. The metric tonne (kg) has sometimes been shown in megagrams (Mg). Some strictly scientific data are presented in SI units only.

To clarify some illustrations, only one set of units is presented on artwork. References in the accompanying text to data in the illustrations are presented in both SI-based and customary U.S. units. On graphs and charts, grids corresponding to SI-based units usually appear along the left and bottom edges. Where appropriate, corresponding customary U.S. units appear along the top and right edges.

Data pertaining to a specification published by a specification-writing group may be given in only the units used in that specification or in dual units, depending on the nature of the data. For example, the typical yield strength of steel sheet made to a specification written in customary U.S. units would be presented in dual units, but the sheet thickness specified in that specification might be presented only in inches.

Data obtained according to standardized test methods for which the standard recommends a particular system of units are presented in the units of that system. Wherever feasible, equivalent units are also presented. Some statistical data may also be presented in only the original units used in the analysis.

Conversions and rounding have been done in accordance with IEEE/ASTM SI-10, with attention given to the number of significant digits in the original data. For example, an annealing temperature of 1570 °F contains three significant digits. In this case, the equivalent temperature would be given as 855 °C; the exact conversion to 854.44 °C would not be appropriate. For an invariant physical phenomenon that occurs at a precise temperature (such as the melting of pure silver), it would be appropriate to report the temperature as 961.93 °C or 1763.5 °F. In some instances (especially in tables and data compilations), temperature values in °C and °F are alternatives rather than conversions.

The policy of units of measure in this Handbook contains several exceptions to strict conformance to IEEE/ASTM SI-10; in each instance, the exception has been made in an effort to improve the clarity of the Handbook. The most notable exception is the use of g/cm³ rather than kg/m³ as the unit of measure for density (mass per unit volume). SI practice requires that only one virgule (diagonal) appear in units formed by combination of several basic units. Therefore, all of the units preceding the virgule are in the numerator and all units following the virgule are in the denominator of the expression; no parentheses are required to prevent ambiguity.
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