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Sharlotte Kramer · Jennifer L. Jordan · Helena Jin
Jay Carroll · Alison M. Beese *Editors*

Mechanics of Additive and Advanced Manufacturing, Volume 8

Proceedings of the 2018 Annual Conference on Experimental and Applied Mechanics

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Editors
Sharlotte Kramer
Sandia National Laboratories
Albuquerque, NM, USA

Helena Jin
Sandia National Laboratories
Livermore, CA, USA

Alison M. Beese
Pennsylvania State University
State College, PA, USA

Jennifer L. Jordan
Los Alamos National Laboratory
Albuquerque, NM, USA

Jay Carroll
Sandia National Laboratories
Albuquerque, NM, USA

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Preface

Mechanics of Additive and Advanced Manufacturing represents one of eight volumes of technical papers presented at the 2018 SEM Annual Conference & Exposition on Experimental and Applied Mechanics organized by the Society for Experimental Mechanics and held in Greenville, SC, June 4–7, 2018. The complete proceedings also includes volumes on *Dynamic Behavior of Materials*; *Challenges in Mechanics of Time-Dependent Materials*; *Advancement of Optical Methods & Digital Image Correlation in Experimental Mechanics*; *Mechanics of Biological Systems & Micro- and Nanomechanics*; *Mechanics of Composite, Hybrid and Multifunctional Materials*; *Fracture, Fatigue, Failure and Damage Evolution*; and *Residual Stress, Thermomechanics & Infrared Imaging, Hybrid Techniques and Inverse Problems.*

Mechanics of Additive and Advanced Manufacturing is an emerging area due to the unprecedented design and manufacturing possibilities offered by new and evolving advanced manufacturing processes and the rich mechanics issues that emerge. Technical interest within the society spans several other SEM technical divisions such as composites, hybrids and multifunctional materials, dynamic behavior of materials, fracture and fatigue, residual stress, time-dependent materials, and the research committee.

The topic of mechanics of additive and advanced manufacturing included in this volume covers design, optimization, experiments, computations, and materials for advanced manufacturing processes (3D printing, micro- and nano-manufacturing, powder bed fusion, directed energy deposition, etc.) with particular focus on mechanics aspects (e.g., mechanical properties, residual stress, deformation, failure, rate-dependent mechanical behavior, etc.).

Albuquerque, NM, USA	Sharlotte Kramer
	Jennifer L. Jordan
Livermore, CA, USA	Helena Jin
Albuquerque, NM, USA	Jay Carroll
State College, PA, USA	Alison M. Beese

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Chapter 1
Structure/Property Behavior of Additively Manufactured (AM) Materials: Opportunities and Challenges

George T. (Rusty) Gray III, Veronica Livescu, Cameron Knapp, and Saryu Fensin

Keywords Additive manufacturing · 304 L SS · Microstructure · Mechanical behavior

1.1 Scope

The certification and qualification paradigms required for additively manufactured (AM) metals and alloys must evolve given the absence of any broadly accepted "ASTM- or DIN-type" AM certification/qualification processes or fixed AM-material produced specifications. This is in part due to the breath of the evolved microstructures produced across the spectrum of AM manufacturing technologies including powder bed and directed energy systems. Accordingly, design and microstructure optimization, manufacture, and thereafter implementation and insertion of AM-produced materials to meet the wide range of engineering applications requires detailed quantification of the structure/property behavior of AM-materials, across the spectrum of metallic AM methods, in comparison/contrast to conventionally-manufactured metals and alloys [1–5]. The scope of this talk is a discussion of some present opportunities and challenges to achieving qualification and certification of AM produced metals and alloys for engineering applications.

1.2 Opportunities

AM of metallic components, as has been detailed by a number of recent reviews [1, 2, 4, 5], can offer opportunities for manufacturing components whose design can be topologically optimized into components that can neither be cast nor readily machined. In addition AM can lead to increased energy efficiency, cost, factory footprint reduction, time savings during manufacturing, and significant material savings for a number of low-volume-high value applications, plus the potential of increased yields from starting feed materials to finished components or subassemblies [1, 2, 4, 5].

1.2.1 Alloy Development

AM to date has been principally focused on utilizing either pure metals or existing engineering alloys available in powder or wire form. Ti-6Al-4 V is a good example of this but so are 2000, 5000, 6000, and 7000-series aluminum alloys. Ti-6Al-4 V is an alloy developed in the 1950's for direct cast applications and/or where an initial cast billet is followed by thermomechanical wrought processing to produce product forms and thereafter machined to produce components with optimized microstructures to meet strength/ fracture toughness/fatigue requirements, in particular for aerospace/defense applications. The compositions of many wrought Ti- and Al-based alloys were optimized to achieve the desired microstructures for either the direct cast or as a prelude to wrought processing following solidification rates typical for cast billets. However, the rapid solidification rates in

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G. T. (Rusty) Gray III (✉) · V. Livescu · C. Knapp · S. Fensin
Los Alamos National Laboratory, Los Alamos, NM, USA
e-mail: rusty@lanl.gov

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laser-powder-bed AM as one example, often in the 10^6 °C per second, are either far too fast or the solidification rates in high-vacuum wire-fed electron beam DED AM processing techniques are far too slow. Alloy development for AM processing cooling rates (both very fast in laser-powder-bed AM favoring atypical microstructures or very slow in wire directed energy deposition AM machines favoring large columnar epitaxial growth yielding poor fracture and fatigue properties) and inert build AM atmospheres enhancing interstitial pick-up affecting properties, each suggest a critical need for funding in alloy design for AM. An example of this need is addressed in a recent publication where a high-strength aluminum powder was functionalized to seed grain nucleation by adding nanoparticles of nucleants, to reduce or eliminate gross epitaxial growth by controlling solidification during AM processing [6].

1.3 Challenges

AM production of metallic components must be bracketed within the scope of the relatively high expense of AM machines, high feedstock (powder or wire) costs, limited build volumes and dimensions at present, slow deposition/build rates, in addition to the evolving certification/qualification procedures/requirements for critical applications [1, 5].

1.3.1 Advances in Powder Production: Chemistry and Cost Reduction

While the cost of cast or wrought alloys of widespread structural industrial importance can vary widely, the cost of powder or wire to support AM production currently ranges from ~2× to ~an order of magnitude more than wrought or cast product at present for many metallic materials. For example, while wrought 304 L SS is currently $6–10/kg, pedigreed 304 L SS powder is ~ $85/kg and while wrought Ti-6Al-4 V is ~$40–50/kg, current ELI-grade Ti-6Al-4 V powder is $300/kg. This substantial cost in the feedstock materials needed for AM, in addition to the substantial financial investments required for AM machine purchase, let alone the operating costs, significantly restricts the market for AM production. As such AM remains centered principally on high-value – low volume component manufacturing where AM can offer unique fabrication approaches not readily available or impossible to produce via direct casting and/or reductive techniques from existing feed stocks. Accordingly, research investment in optimized /high volume and yield/reduced cost powder production technologies is a promising opportunity that is crucial if AM is to be expanded from its current restriction to low-volume high-value component manufacturing applications.

1.3.2 AM Technologies Produce a Spectrum of Microstructures

Given the differences in feedstock employed and the melting and solidification rates between laser versus electron-beam and powder-bed versus DED techniques, it is not surprising that a spectrum of microstructures can be developed by different AM platforms [1, 2, 4]. An illustration of the spectrum of microstructures and properties produced by laser or electron-beam powder-bed, directed-energy-deposition (DED) techniques such as laser-directed energy powder fed or electron-beam wire fed machine AM produced 304 L SS in comparison to wrought is presented in Fig. 1.1.

Electron-backscatter diffraction (EBSD) images of the microstructures from an ASTM-spec. wrought plate of 304 L SS and the microstructures of identically sized AM-304 L SS plates produced on four different AM machines utilizing identical 304 L SS chemistry powder are given in Fig. 1.1. The microstructures of the wrought versus the 4-AM 304 L SS plates are seen to be significantly different. While the wrought 304 L SS displays an equiaxed-polycrystalline grain structure, the microstructures of the four different AM produced 304 L SS display a spectrum of microstructures in terms of both length scale as well as the degree of morphological anisotropy. With the exception of the ARCAM build, each of the other three AM builds exhibit anisotropic elongated larger grain structures aligned with the long axis of the grains parallel to the AM build direction consistent with the solidification direction during the build. Although structure-property data probing many PSPP relationships is important in qualifying AM products, a major concern remains when comparing AM parts with those made using traditional metal manufacturing methods, in particular the failure and damage mechanisms that arise from the unique microstructures produced during AM.

Further, efforts to formulate a rigorous roadmap to the certification and qualification of AM metals and alloys is impeded by: (1) a lack of systematically quantified processing/structure/properties/performance (PSPP) data covering even a small