JOM, Vol. 68, No. 3, 2016
DOI: 10.1007/s11837-015-1799-4

Additive Manufacturing in the Minerals, Metals, and Materials Community: Past, Present, and Exciting Future

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Engineering is entering a new era of design disruption driven by new technologies, led by additive manufacturing, which is smashing the physical and virtual world together and has huge potential to disrupt current manufacturing process paradigms. This new paradigm is part of the emerging Third Industrial Revolution that is combining digital and physical processes in new ways.[1]

In this context, the role of the minerals, metals, and materials community becomes clear: to imagine, develop, and scale the materials and processes that will empower the expansion of digital industrial technologies. The goal of this special topic, Progress in Additive Manufacturing, is to provide a forum demonstrating the depth and breadth of the research and development activities across manufacturing technology that most epitomizes that goal: additive manufacturing.

It is with great pleasure that I present the follow-up installment from the March 2015 *JOM* special topic.[2] The year 2015 produced many exciting developments in the field, including new applications and continued market growth in additive for engineering materials, particularly metals.

In many ways, the excitement and emphasis on additive manufacturing of metals and industrial materials is the product of more than 20 years of effort. As early as 1993,[3] demonstrations were completed concerning the feasibility for binderless sintering of metal powders. It is interesting to note the process and material advancement in laser powder bed fusion between then and now, as shown in Table I.

The example of the dramatic improvement in laser powder bed fusion of metals is illustrative of the advancement for the field including progress towards industrial implementation. This trend can also be extended to other technologies like directed energy deposition, cold spray, and other processes.

This foundation of advanced process development has led to an exciting number of new applications emerging in additive manufacturing over the past year. Figure 1 shows an example from the aerospace industry and is the first FAA-certified fully additive component for use in GE commercial aviation gas turbine engines.[5] The component is a housing for the compressor inlet temperature sensor that protects sensor electronics from icing and airflow in service. The motivation for additive manufacturing in this case is design freedom and consolidation of an assembly. Figure 2 is an example of an emerging concept for water desalinization.[6] This component is an additively manufactured rotor, roughly 6 inches (c. 15 mm) long, which is being used to demonstrate cost-effective water and salt separation. Perhaps the most exciting development has been the recent type certification of the LEAP-1A jet engine in late 2015,[7] which includes 19 fuel nozzles produced by additive manufacturing. With the key milestone of certification complete, the engine is on schedule for full rate production including additive manufacturing of many thousands of components per year. The success of industrial implementation of additive technology in the aerospace industry is paving the way for broader applications in other industries such as oil and gas.[8]

There are many tailwinds for industrial implementation of additive technology. In contrast to as recently as 5 years ago, there are multiple machine producers across many process modalities with greater flexibility and willingness to customize hardware for specific applications. As noted above, this has resulted in game changing high performance products emerging in oil and gas, aerospace and power-generation industries using the unique capabilities of additive manufacturing in material

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(Published online January 8, 2016)

Table I. Comparison of process parameters for laser powder bed fusion[3,4]

	1993[3]	2015[4]
Laser power	7.5 W	200–1000 W
Spot size	0.5 mm	0.1 mm
Scan speed	2 mm/s	1000 mm/s
Layer thickness	100 μm	20–50 μm
As-built density	30%	>99.9%

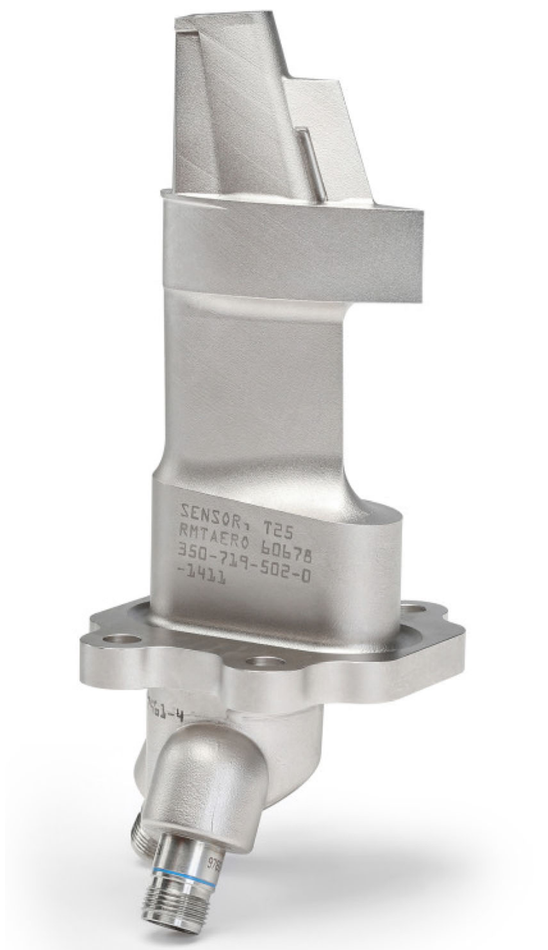

Fig. 1. Inlet temperature sensor housing for jet turbine engine, roughly 3″ (c. 7.5 mm) tall.[4]

intensive applications. These trends continue to grow the design entitlement for additive manufacturing technologies.

Despite those growth trends, there remain headwinds that are well suited for the minerals, metals, and materials community to tackle. A key barrier is expensive qualification of a new materials and process combinations. It can easily take over 5 years to qualify for industrial use one new material manufactured using a specific process. This is an area where the community can gather to develop

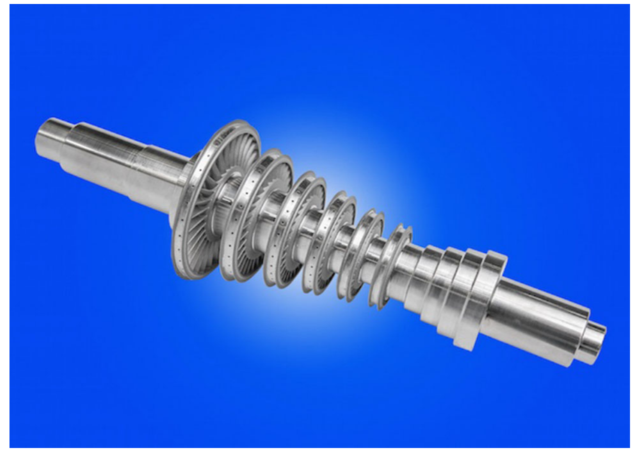

Fig. 2. Additively manufactured rotor for water desalinization, roughly 6″ (c. 15 mm) in length.[5]

new rapid qualification strategies incorporating fundamental process and property understanding with integrated computational materials engineering approaches. ICME frameworks and codes that efficiently model complex additive manufacturing processes in weeks and days is a strong need. More work on understanding not just average material properties but also defect populations will be essential. Another key barrier is the development of new machines that are production ready and can produce material reliably in large volumes. Collaboration with the materials community is essential to inform the advancement of machines from prototype to full production. Again, a thorough understanding of material defect populations and sensitivities for varying process variables will serve as the foundation for eclipsing this barrier.

As a greater number of materials and process combinations come to be well characterized and the machines supporting them become industrially hardened, adoption of additive manufacturing will expand. With that change, product designers will become empowered to select tailored material and process combinations that drive performance improvement for demanding applications. This will have far-reaching impacts that accelerate the introduction of new, higher-performing products that will support the global infrastructure for years to come. In my opinion, this is the most exciting time and most exciting technology in the history of materials engineering.

It is my belief that the TMS community, with its unique balance of members from academia, government, and industry, can provide critical leadership in this enabling technology. A cross-section of work of interest to this community is included in the papers that follow. The topics range from directed energy deposition of titanium to laser powder bed fusion of steel, and include a new approach to additive machine architecture and binder jetting of ceramics. Taken together, this special topic demonstrates the depth and breadth of research and development activities in additive manufacturing across the spectrum of metals and ceramics.

The following papers are included in this special topic: Progress in Additive Manufacturing. To download any of the papers, follow the url http://link.springer.com/journal/11837/68/3/page/1 to the table of contents page for the March 2016 issue (vol. 68, no. 3).

- "Review of Mechanical Properties of Ti-6Al-4V Made By Laser-Based Additive Manufacturing Using Powder Feedstock" by Allison M. Beese and Beth E. Carroll
- "Fatigue Performance of Powder Metallurgically (PM) Manufactured Ti-6Al-4V Alloy: A Critical Assessment and Metallurgical Approaches for Improving Fatigue Strength" by Fei Cao and K.S. Ravi Chandran
- "Overview of Materials Qualification Needs for Metal Additive Manufacturing" Mohsen Seifi, Ayman Salem, Jack Beuth, Ola Harrysson, and John J. Lewandowski
- "Evaluating the Effect of Processing Parameters on Porosity in Electron Beam Melted Ti-6Al-4V via Synchrotron X-ray Microtomograp" by Ross Cunningham, Sneha P. Narra, Jack Beuth, and A.D. Rollett
- "Texture Evolution During Laser Direct Metal Deposition of Ti-6Al-4V" by Niyanth Sridharan, Anil Chaudhary, Peeyush Nandwana, and Sudarsanam Suresh Babu
- "Understanding the Microstructure Formation of Ti-6Al-4V during Direct Laser Deposition via In-Situ Thermal Monitoring" by Garret J. Marshall, W. Joseph Young II, Scott M. Thompson, Nima Shamsaei, Steve R. Daniewicz, and Shuai Shao
- "The Influence of Surface Topography on Mechanical Properties of Ti-6Al-4V Additively Manufactured by Selective Electron Beam Melting" by Y.Y. Sun, S. Gulizia, C.H. Oh, D. Fraser, M. Leary, Y.F. Yang, and M. Qian
- "A Honeycomb-Structured Ti-6Al-4V Oil–Gas Separation Rotor Additively Manufactured by Selective Electron Beam Melting for Aero-Engine Applications" by H.P. Tang, Q.B. Wang, G.Y. Yang, J. Gu, N. Liu, L. Jia, and M. Qian
- "Accelerating Industry Adoption of Metal Additive Manufacturing Technology" by Ken Vartanian and Thomas McDonald
- "Analysis of Glass-Filled Nylon in Laser Powder Bed Fusion Additive Manufacturing" by John Slotwinski, Erin LaBarre, Ryan Forrest, Emily Crane
- "Additive Manufacturing of Reactive In Situ Zr Based Ultra-High Temperature Ceramic Composites" by Himanshu Sahasrabudhe and Amit Bandyopadhyay
- "Process Development of Porcelain Ceramic Material with Binder Jetting Process for Dental Applications" by Hadi Miyanaji, Shanshan Zhang, Austin Lassell, Amirali Zandinejad, and Li Yang
- "Experimental Study of Disruption of Columnar Grains during Rapid Solidification in Additive Manufacturing" by Guha Manogharan, Bharat Yelamanchi, Ronald Aman, and Zaynab Mahbooba
- "Microstructure and Corrosion Resistance of SLM 316L Stainless Steel" by Jason R. Trelewicz, Gary Halada, Olivia K. Donaldson, and Guha Manogharan
- "Effects of Powder Attributes and Direct Metal Laser Sintering (DMLS) Process Conditions on the Densification and Mechanical Properties of 17-4 PH Stainless Steel" by Harish Irrinki, Michael Dexter, Brenton Barmore, Ravi Enneti, Somayeh Pasebani, Sunil Badwe, Jason Stitzel, Rajiv Malhotra, and Sundar V. Atre
- "A Metallurgical Evaluation of the Powder-Bed Laser Additive Manufactured 4140 Steel Material" by Wesley Wang and Shawn Kelly

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