ADVANCED MANUFACTURING: NAVIGATING THE PATH FORWARD

Highlights from a member survey and panel discussion outlining the challenges and benefits of advanced manufacturing for the materials community.

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The core elements of advanced manufacturing are embodied in the pillars of Industry 4.0[1-3] (Fig. 1). These pillars, when seamlessly integrated, enable innovative product designs, and the agile and rapid production of parts at reduced cost. Seamless digital data connectivity and interoperability is required to leverage the benefits of Industry 4.0[4]. While there is no single authoritative definition of advanced manufacturing, the National Science and Technology Council, Subcommittee on Advanced Manufacturing has stated, "Advanced manufacturing is defined as the innovation of improved methods for manufacturing existing products, and the production of new products enabled by advanced technologies"[5].

Recognizing that materials and processes are integral to achieving the full potential of advanced manufacturing, members of ASM International came together to explore, and to better understand, how the Society could effectively serve the community. This paper reports on the results of three initiatives of the ad hoc Advanced Manufacturing Committee.

1. A membership survey was conducted to better understand the needs of the advanced manufacturing community.
2. The Committee organized a panel discussion entitled "Advanced Manufacturing: Progress and Opportunities" at IMAT 2022 in New Orleans on September 13, 2022, to explore key elements of advanced manufacturing and solicit member feedback.
3. A new Advanced Manufacturing Technical Committee is being formally stood up.

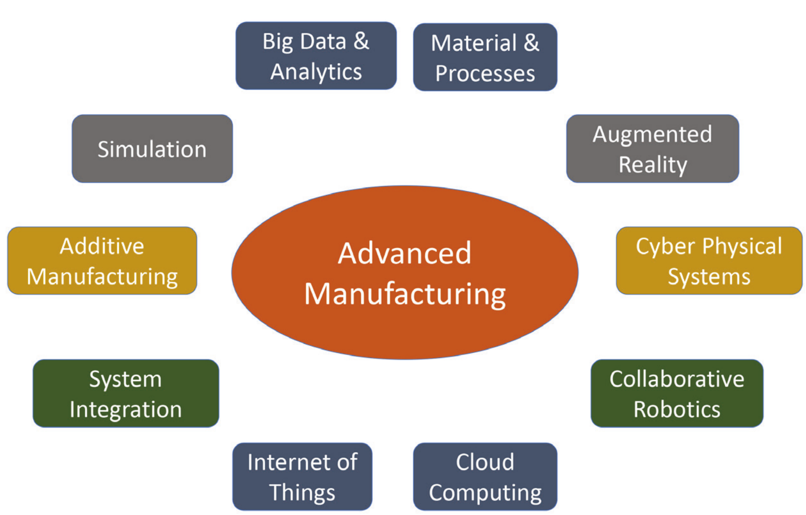

Fig. 1 — Advanced manufacturing in Industry 4.0.

**Member of ASM International*

SURVEY RESULTS

An online survey of ASM members was conducted in July and August 2022 to better understand the interest and needs of members in advanced manufacturing. The survey was sent to ASM volunteer leaders active in chapters, affiliate societies, and committees. One hundred and thirty-nine responses were received. The survey results were assessed and scored based on assigning weights to Likert scale responses.

Six questions were posed. Those surveyed were given the opportunity to choose from several responses and provide written responses and comments. The numerical results are present in Tables 1-6. A sampling of the written comments submitted is presented below each table.

TABLE 1 — WHAT ARE THE MOST IMPORTANT DISTINGUISHING FEATURES OF ADVANCED MANUFACTURING TECHNOLOGIES?

Ability to manufacture new part configurations	214
Improved properties and performance of parts	213
Enhanced quality/accuracy/traceability	203
Cost efficiency	197
Ability to manufacture custom parts / smaller production runs	195
Connectivity with sensors, instruments, and other devices ("Internet of Things")	192
Data generation, capture, and analysis	189
Integration with computational engineering/digital twin capability	189
Cycle time reduction	188
In-process sensing/feedback	183
Increased throughput/productivity	183
Use of automation/robotics	167
Use of artificial intelligence/machine learning	167

Comments:

"Producing product characteristics/properties unattainable by existing technologies."

"Reliability and repeatability in manufacturing process."

"Full life cycle capability. Smaller players should be able to compete."

TABLE 2 — WHICH MANUFACTURING/PROCESSING AREAS ARE MOST SIGNIFICANTLY IMPACTED BY ADVANCED MANUFACTURING?

Additive manufacturing	244
Laser processing	190
Machining	183
Surface engineering / modification	181
Welding brazing, soldering, bonding, mechanical fastening	166
Nanotechnology	165
Powder metallurgy	165
Coating (e.g., thermal spray)	160
Casting	149
Forming	142
Heat treating	140
Forging	129
Primary processing	116

Comments:

"All materials processing methods can be involved in Advanced Manufacturing…"

"This list is too focused on metals; need to expand to include manufacturing of polymers, ceramics, and semiconductors (electronic systems)."

TABLE 3 — WHICH MATERIALS CATEGORIES ARE MOST SIGNIFICANTLY IMPACTED BY ADVANCED MANUFACTURING?

Gradient-structured materials	209
Advanced composites	201
Superalloys	195
High-entropy alloys	189
Light alloys (e.g., aluminum, titanium)	184
Ceramics and ceramic-matrix composites	180
Plastics/polymers	173
Stainless and high alloy steels	172
Carbon-based materials (e.g., carbon nanotubes)	159
Tool steels	150
Carbon and alloy steels	145

Comments:

"Advanced manufacturing methods should be focused on the 'difficult to make' materials in the most demanding applications."

"Since all materials areas can be significantly impacted by advanced manufacturing—depending upon part and heat lot size, quantity, cycle time, etc.—it's hard to generalize at this level."

TABLE 4 — WHAT ARE THE GREATEST CHALLENGES IN IMPLEMENTING OR REALIZING BENEFITS OF ADVANCED MANUFACTURING TECHNOLOGIES?

Qualification and certification of processes or parts	193
Cost of equipment transition	193
Lack of standards	190
Technology maturity/stability	184
Data findability, accessibility, interoperability, reusability	182
Access to information/knowledge management	174
Risks/unknowns	166
Organization bandwidth, resource constraints	158
Personnel training	158
Disruption to existing processing routes	150
Intellectual property issues, access to proprietary technology	147
Personnel availability	146
Cybersecurity concerns	139

Comments:

"Cultural/corporate aversion to change."

"Time and money required to scale up new technologies from lab to mass manufacturing."

"Partnerships among companies and academia and government agencies will be critical to making smooth transitions into various arenas of adv. mfg."

TABLE 5 — WHAT TOOLS OR TECHNOLOGIES ARE IN GREATEST NEED OF ENHANCEMENTS TO REALIZE THE BENEFITS OF ADVANCED MANUFACTURING?

Materials processing and properties data	220
Process simulation tools that can more accurately mimic reality	206
Noncontact inspection tools (blue light, CT scan, etc) to minimize process variation and qualify parts	197
Artificial intelligence / machine learning	181
Digital thread capability (integration and traceability through a product's lifespan)	181
Digital twin capability (accurate digital representation of physical systems)	179
Data management tools	174
CAD model-based definition design tools	164

Comments:

"Data acquisition and statistical tools for improvement of production efficiency and product reliability."

"In situ process monitoring."

"Inspection in general, as there will now be complex parts with no way to inspect internal features using conventional metrology."

"We have very good AI/ML strategies, but they are mostly relegated to other industries or as case study examples in academic problems."

"NDT capable of finding flaws reliably so that engineers can complete damage tolerance and other life prediction analysis."

"Adaptable virtual inspection methodologies that dynamically update to adjust to process improvements and changing production requirements."

"Tools that correlate simulation outputs, actual test data, and validation results."

JOIN THE DISCUSSION

The theme of the International Materials, Applications & Technologies (IMAT) 2023 (October 16-19, Detroit) conference is "Advanced Materials and Manufacturing Technologies." Papers are invited on a broad range of topics related to advanced manufacturing and Industry 4.0. Abstracts are due by February 24, 2023. Visit: asm.confex.com/asm/imat2023/cfp.cgi.

TABLE 6 — WHICH OF THE FOLLOWING IS MOST IMPORTANT FOR ASM INTERNATIONAL TO MAKE THE GREATEST POSITIVE IMPACT IN ADVANCED MANUFACTURING?

Development of standards (in collaboration with standards organizations)	212
Advanced Materials & Processes technical articles	194
ASM Handbook content	194
Conference programming	190
Data sets	186
ASM Technical Books	186
Connections to consultants or expert resources	177
Education courses (online, virtual, self study)	177
Failure analysis content and case histories	175
Education courses (in person)	172
Support for undergraduate or graduate student projects	165
Digital tools / software	162
Webinars	155
Video content	137

Comments:

"Priority 1—understand the needs of members (just like this survey—great work!)."

"The focus clearly needs to be on materials-related activities, but there are other societies/disciplines that have an interest in this topic (e.g., mechanical engineering); so collaboration with them would be beneficial to the overall success of such an initiative."

"Industry 4.0, advanced analytics, machine learning, automation."

"Hybrid manufacturing using expanded menu of materials."

"Standardization, definitions, data, machine language readability/interoperability, materials."

"Organize conference symposia, generate webinars, create networking events, publish in *AM&P* to update the community."

"…there are a lot of multidisciplinary topics to cover, so it is imperative that the ASM Advanced Manufacturing Committee bring in the business and science leaders in the different fields to identify/confirm any common challenges."

From the responses provided, several salient conclusions can be drawn. ASM members believe in the importance of advanced manufacturing. Advanced manufacturing will impact a wide range of materials and processes. The challenges associated with implementing advanced manufacturing include qualification and certification of new processes as well as effective digital data capture and management. To enable advanced manufacturing quality digital material and process data sets are required as are modeling and simulation tools. Artificial intelligence (AI) and machine learning (ML) methodologies are viewed as important means of process development, optimization, and qualification.

PANEL DISCUSSION & BRIEFS

The Committee organized a panel discussion entitled "Advanced Manufacturing: Progress and Opportunities." The panel was held at IMAT 2022 in New Orleans on September 13, 2022. Perspectives on advanced manufacturing were briefed by four renowned experts, Prof. Jack Beuth, Prof. Glenn Daehn, Dr. Dave Furrer, and Mr. Michael "Mick" Maher (Fig. 2). Subsequently, a robust and audience interactive discussion was moderated by Dr. William E. Frazier. Key elements of advanced manufacturing technology were explored along with the steps required to secure the promise of Industry 4.0. This section summarizes the main points by the panel.

(continued on page 28)

Frazier Beuth Daehn Furrer Maher

Fig. 2 — Panel members, Advanced Manufacturing: Progress and Opportunities.

HAMMER – Hybrid Autonomous Manufacturing: Moving from Evolution to Revolution

Prof. Glenn Daehn
The Ohio State University

The modern engineer must think both in terms of bits and atoms. Digital design and manufacturing are now the mainstream expectation. Computer numerical control (CNC) machining was the first step in this journey, and the same basic path planning and 3D rendering has been used to support additive manufacturing (AM). There is now much focus on optimizing the materials that are produced by additive manufacturing, as well as collecting data to sense possible defect locations, and expanding the library of available materials. Both CNC machining and additive manufacturing are methods that are primarily for shape making. Plastic deformation is the other obvious way to make shapes – and thermomechanical processing, which also involves deformation, is our community's standard tool for improving materials properties. One point raised during this session is that we should have a digital analog for making shapes via deformation as we have for CNC machining and additive manufacturing. Such a tool could resemble a robotic blacksmith. This automaton could at once both create target shapes by deformation and improve microstructure—as the human blacksmith does. Deformation processing also generally has a much lower embodied energy per mass than the creation of parts by additive or subtractive processing. Another advantage of deformation is it scales to large sizes with commercially available robots and presses, enabling the creation of parts orders of magnitude larger than a human could manufacture. This approach has been developed and written in a *Metamorphic Manufacturing* report (available at tms.org/metamorphicmanufacturing)[6].

In recent months, a team of researchers from Ohio State (led by Daehn), Northwestern University (Jian Cao, leader), Case Western Reserve University (John Lewandowski, leader), University of Tennessee Knoxville (Tony Schmitz, leader), and North Carolina Agricultural and Technical University (Jag Sankar, leader) went deeper into the basic ideas of how we manufacture structural components and came to realize that addition, subtraction, deformation, transformation, inspection, and positioning represent the universe of basic operations that are executed to develop manufacturing processes and all can be done incrementally, usually with simple equipment. We can break these operations down and reassemble these like code and subroutines. This is at the heart of a newly funded NSF Engineering Research Center HAMMER: Hybrid Autonomous Manufacturing—Moving from Evolution to Revolution (see hammer.osu.edu). We envision a future of manufacturing for design, where for example, a preform could be created by inexpensive high-throughput processes such as wire-arc additive manufacturing of a multimaterial preform or by welding similar or dissimilar metallic volumes and then use thermomechanical precision open-die forging processing to fabricate a near-net shape with tailored local properties. Critical dimensions could be

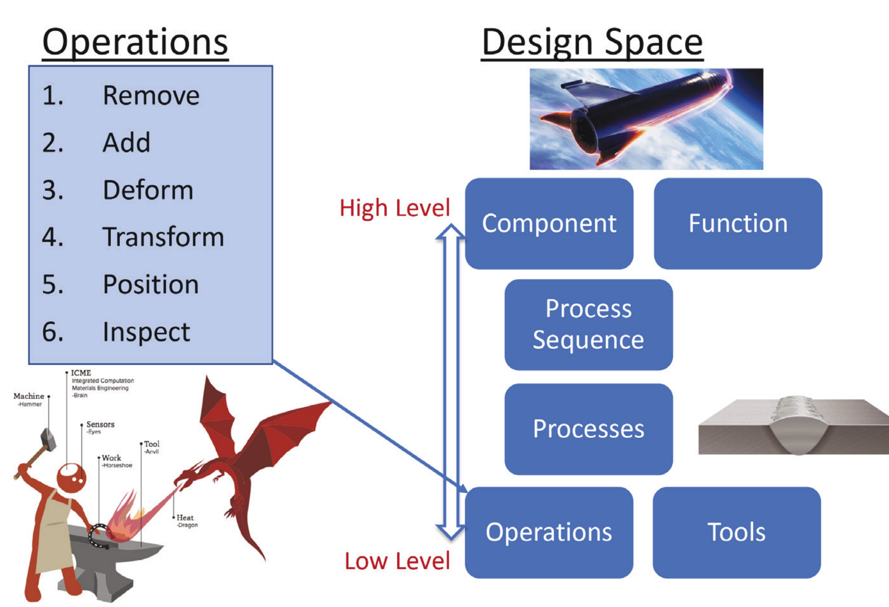

Fig. 3 — Hybrid autonomous manufacturing.

finished machined and in-situ sensing provides data that can be used for quality assurance.

This brings us back to the discussion of physical atoms and digital bits. If this fabrication sequence is automated and interoperation transfer is simple and low-cost, the whole process for making the part becomes very akin to software, where processes like additive manufacturing are mere subroutines in a larger program, executed to make a part. This represents a paradigm of manufacturing for design. When the part is created, the data flow is then used to qualify this part, ideally through model-based certification. In addition, this data (along with physical test results) from the fabricated component can also be used to improve the certification models as well as the control algorithms. This is the role of machine learning. Achieving these goals will require traversing a long and challenging path, but one that our new Engineering Research Center is committed to follow. This represents a paradigm of manufacturing for design where process and product design are simultaneously optimized within constraints. The elements of this problem are noted in Fig. 3.

Perspectives on Advanced Manufacturing

Dr. David Furrer
Pratt & Whitney

Advanced manufacturing is changing the way we think about design and new product creation. There are several enabling technologies and capabilities that are making advanced manufacturing possible, including: rapid and accurate computational material and process modeling, advanced sensors, manufacturing informatics, and model guided and assisted qualification and certification. These foundational technologies are enabling new product capabilities and are radically changing how products are produced.

The well-known industrial revolutions have each provided for new capabilities that have changed how materials and components are manufactured.

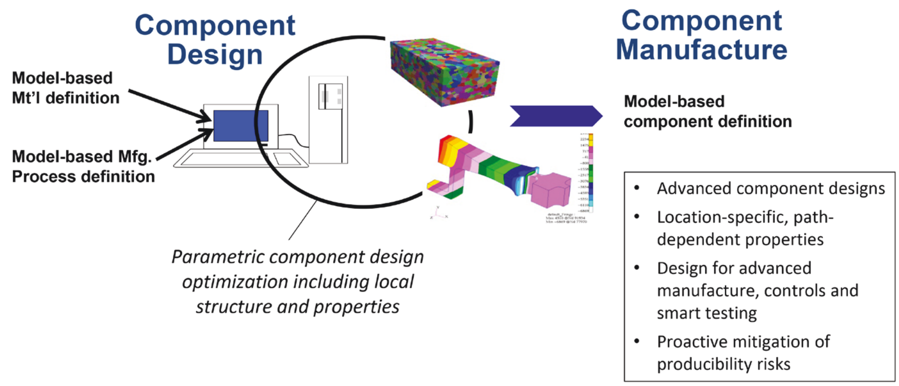

Fig. 4 — Model-based material, process, and component definitions for advanced digital manufacturing.

Industry 3.0 has largely been focused on and has delivered computerization and advanced automation. Industry 4.0 is currently focused on advancing simulation, digital data, adaptive controls, and continuous learning through artificial intelligence and machine learning methods. The current stage of the industrial revolution is manifested by the rapid development of advanced manufacturing technologies that provide a framework for digital engineering, manufacturing, communication, and optimization, including validation and certification.

It is well known that materials and subsequent component properties are developed through specific manufacturing process paths. Local component properties can be understood as being controlled by location-specific processing conditions, including thermal, mechanical, and time dependent parameters (e.g., strain, strain rate, cooling rate). Computational models have matured to the point where they are utilized for virtually all advanced manufacturing processes. Similarly, materials models are becoming available with the capability to accurately predict the microstructure evolution and associated mechanical properties based on specific manufacturing processing paths. The ability to describe and define materials and manufacturing processes by means of model-based definitions enables true holistic model-based component definitions, which in turn provides for a number of critical capabilities now afforded through the application of digital engineering and advanced manufacturing (Fig. 4).

The application of advanced manufacturing methods provides for greater control of properties on a component location-specific basis. Enhanced understanding of spatial distribution of mechanical properties and ability to control local mechanical properties provide a means for design engineers to further optimize component designs and product applications. Knowledge of systematic, physics-based spatial variation in material properties can provide for the development and utilization of smart testing, which targets critical locations that provide greatest insight into component capabilities and underlying manufacturing process control. Smart testing is a means of evaluating products and validating models and predicted local properties. This approach can readily support rapid qualification and certification of new components and manufacturing processes.

Additive manufacturing is leading the charge in many areas of advanced manufacturing, including computational modeling, process design optimization, advanced sensors, and smart testing. Examples of integrated computational modeling in the design, manufacturing, and testing of AM components are becoming more prevalent. The culmination of the enabling technology elements will continue to drive advanced manufacturing methods forward for the benefit of the community as a whole.

Process Monitoring and Machine Learning in Additive Manufacturing

Prof. Jack Beuth
Carnegie Mellon University

Process monitoring must be viewed in terms of the physical phenomena being observed. With laser powder bed fusion (LPBF) processes, some physical phenomena of interest include (i) melt pool spatter, (ii) pore defects, (iii) re-coater blade collisions, (iv) thermal nonuniformity and thermal drift, and (v) registering data to the location in the build. Spatter detection in LPBF is important to the understanding of defect evolution. This can be done with high-speed video cameras in combination with technologies that can automatically track particle trajectories. Some observations from work done at Carnegie Mellon University are (i) lack of fusion can induce more spatter; (ii) keyholing radically increases spatter; (iii) build rates that are too fast or too slow can increase spatter; and (iv) scan strategies with more starts and stops can increase spatter.

For directed energy deposition wire fed processes, machine learning of melt pool video data has been used to identify irregularities with minimal training sets. ML and artificial intelligence are needed for analysis because of the huge data sets available. ML and AI are useful in making design choices and for parameter selection, for process monitoring and control, and for the analysis of images and materials characterization data.

The integration of ML tools across the additive manufacturing data ecosystem is of potential high value. The AM ecosystem may be divided into preprocessing, processing, and post processing. The preprocessing phase involves the design and development of new materials and macrostructures. In this phase, process design optimization, powder characterization, process map optimization, and the development of multimaterial structures and novel lattice materials can be accomplished. During the processing phase, in situ sensor data can be analyzed and used for process monitoring and control, as well as for flaw detection. Post process applications include defect and surface finish characterization.

Challenges with Adopting Digital Manufacturing Technologies

Mr. Mick Maher
Maher & Associates LLC

While the benefits of utilizing digital manufacturing technologies such as Internet of Things (IoT), AI/ML, and computational modeling and simulation are numerous, many companies are struggling to adopt them. Incorporating digital based systems into traditional manufacturing operations is extremely disruptive. It requires thorough planning and comprehensive buy-in from across the organization to be successful. To do this well, companies need to be aware of the challenges that will be faced. In adopting digital manufacturing technologies, the challenges most likely to be faced can generally be related to strategy, business case, infrastructure, resources, data management, and business practices.

Companies need a holistic strategy to guide the adoption of digital manufacturing. Common mistakes range from having no strategy to failing to understand their internal operations and the extent of effort required for full utilization. The strategy needs to tie overarching business goals to the solutions sought. In addition to having a clear understanding of the value that “digital” brings to their operations, management should be keenly aware of the task at hand and the effort that will be required. Change management is key to preparing the workforce and being able to maintain momentum through the successes and failures that occur in any change.

Adoption of digital manufacturing technologies can be difficult, but a solid business case helps focus the effort. Business cases tend to focus on incremental changes. To fully realize the benefits touted for digital manufacturing technologies, the business cases need to look at the global changes brought about due to the pervasive impacts these technologies have on the organization. Business cases can often underestimate the effort required, which undermines the adoption when overly optimistic goals are missed. At the same time, secondary and tertiary impacts are often excluded from the analysis.

Companies need to assess their current infrastructure and resources. Connectivity is a key requirement for digital manufacturing technologies. Without a clear overarching strategy for implementation, the company can become burdened with and overwhelmed by multiple, standalone computational systems requiring their own specialists and support. Understanding the existing workforce and infrastructure helps identify training and talent acquisition needs, as well as areas of investment to ease the transition to an optimum digital state for manufacturing operations. Implementations are often very site-centered, but to fully take advantage of the digital environment, the entire supply chain should be considered a resource that needs to be connected into the system. Cyber-physical security of the infrastructure and data need to be addressed to minimize the risks inherent in the use of digital manufacturing technologies. In fact, data management is a challenge that is often overlooked until the problem becomes overwhelming. In adopting these technologies, a clear policy is required that not only addresses security but includes data volume, relevance, storage, and accessibility.

A company’s business practices can become a challenge. The impact of tech data package ownership, qualification, and certification, in addition to intellectual property as related to adoption of digital manufacturing technologies and changes to these practices, need to be considered. In a similar vein, companies have not adapted to an ever-shrinking technology cycle. There is an assumption that implementing these technologies is a one-time event, and this perspective does not consider the need for a technology refresh rate and how to incorporate that into policy. Finally, while incorporating digital manufacturing technologies can provide huge benefits to increasing efficiencies, it is imperative to include information technology personnel early and often in the process.

ADVANCED MANUFACTURING TECHNICAL COMMITTEE

An ASM International ad hoc Advanced Manufacturing Technical Committee was formed over the course of the past year. The committee's charter and membership are currently in the process of being formalized for review and approval by the Board of Trustees. Those interested in participating in the committee are welcome. Contact Scott Henry at scott.henry@asminternational.org for more information.

The purpose of the committee is to provide the volunteer leadership and coordination required to ensure that the Society is serving the needs of its members and the broader materials, processing, and manufacturing community. As such, the committee is charged with stimulating the development and disseminating of valuable and accurate programming, information, education resources, and data required for the scientific advancement and practical application of advanced manufacturing technologies.

The committee is committed to establishing and executing a process for the delivery of a continuous stream of value-added products and promoting the professional development and maturation of advanced manufacturing personnel spanning the continuum of their professional careers. As part of its mission, the committee will address issues of global importance to ASM members, e.g., clean energy production, environmental impact, economic viability, workforce development, and sustainability.

SUMMARY

Advanced manufacturing rests on the pillars of Industry 4.0 (Fig. 1). To realize the benefits of advanced manufacturing, new, innovative materials and processes must be developed concomitantly. The benefits of advanced manufacturing include low cost, rapid, product development, manufacturing agility, product customization, and feature-specific tailored properties. It also enables novel designs that were previously unable to be conventionally manufactured. Key enablers include effective data management. FAIR data management principles (findable, accessible, interoperable, and reusable) must be implemented[4]. Advanced physics-based modeling and simulation tools (e.g., integrated computational materials engineering, ICME) and analytic tools such as AI and ML will help accelerate the qualification of processes and the certification of products. It is important to recognize that the challenges associated with the successful implementation of advanced manufacturing are multifaceted and involve political, economic, social, and technological (PEST) issues. How best to overcome these obstacles is the focus of the new ASM committee. **~AM&P**

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