



## MEETING SUMMARY

### **[America Makes & ANSI Additive Manufacturing Standardization Collaborative \(AMSC\)](#) *The Current and Future Landscape for Additive Manufacturing (AM) Feedstock/Precursor Materials Standardization***

Tuesday, July 13, 2021, 11:00 am – 3:30 pm Eastern

This virtual event brought together subject matter experts for a discussion intended to help to further develop and refine the AMSC [Standardization Roadmap for Additive Manufacturing](#), last published in June 2018. This includes discussion of the following:

- What are the attributes of AM feedstock/precursor materials that lend themselves to standardization?
- What is currently happening or needs to happen in terms of standardization of metals, polymers, ceramics, composites, etc.?

Presentations from the event are available as a [single zip file \(60MB\)](#) and are available for [individual download here](#). The embedded links in the remainder of this report point directly to the individual presentations.

- View the [Final Draft Agenda](#) and [Speaker Bios](#).

#### **Discussion Topic and Speaker**

##### **Welcome**

##### **Jim McCabe, Senior Director, Standards Facilitation, ANSI**

Mr. McCabe welcomed participants, noting that today's meeting is part of a series of events aimed at helping to capture the current and desired future landscape for additive manufacturing standardization. This includes updates on progress by standards developing organizations (SDOs) and others to address the gaps identified in the AMSC standardization roadmap, today specifically related to different types of feedstock materials.

##### **Brandon Ribic, Ph.D., Technology Director, America Makes**

Brandon Ribic welcomed participants, adding that our goal is to foster collaboration and coordination on standardization across the community, where we've been and where we're going.

#### **Session 1: Presentations on Industry Standards and Guidance Documents**

##### **Moderator: Jim McCabe, Senior Director, Standards Facilitation, ANSI**

Jim McCabe invited each of the speakers to make their presentations and answer questions submitted by audience members. (**Note: throughout this report, speaker remarks are abbreviated and summarized to note key points.**)

##### **J. Hector Sandoval, Fellow, Lockheed Martin (SAE International) [Presentation Link](#)**

Hector Sandoval provided an overview of the work of the SAE International AMS-AM committee on additive manufacturing for aerospace, which he chairs. He reviewed the committee's composition and specifications that have been published and that are in development, including AM feedstock materials for metals. The committee is organized around three subcommittees for metals, non-metallics, and repair. AMS7002 governs the process requirements for the production of metal powder feedstock for use in AM of aerospace parts. There are also standards specifying the requirements needed to support certification of the feedstock material and the part. The non-metallics subcommittee has produced process and material specifications for fused filament fabrication.

Other notable metallics specifications include AMS7025 on metal powder feedstock size classifications and AMS7031 on process requirements for recovery and recycling of metal powder feedstock for use in AM of aerospace parts. The group is also creating aerospace specifications and guidelines documents to control the requirements for powder distributors and templates so that they can create additional feedstock specifications for the different types of alloys: nickel, aluminum, titanium, and steel. Specifications are developed at the request of a technical sponsor typically supported by three other companies/members in response to an industry need. The committee anticipates that work going forward will include ceramics and other materials.

Mr. Sandoval described the SAE framework that applies to AM specifications for all processes and materials. It depends on the development of a process control document (PCD) for the key variables of a given AM process and for production of the feedstock material to enable certification of the resulting part. All material and process specifications have requirements for data submittal. Data is submitted to Battelle/MMPDS which generates an S basis value that can be used for lot acceptance of the material and for quality assurance. The technical sponsor may make the PCD follow a proprietary process to protect its IP or publish the PCD as a public standard. While the SAE specifications have the lot acceptance values, the MMPDS handbook Volume II will include design values for additive manufacturing.

In addition to the work of the SAE AMS-AM, the SAE ITC has an AM data consortium (AMDC). It has company membership and generates AM data for specification minimums. This is important because some companies view the data related to a part specification as proprietary and do not like to share it. Data can also be obtained from groups like America Makes. Long-term, there will be a repository for design data for analyses, trade studies, and certification properties for material specification minimums. Folks are invited to join the AMS-AM as individuals or have their companies join the AMDC.

#### **Q&A**

**You mentioned ceramics being a future opportunity under consideration for standards development. Can you talk more about ceramics and how those opportunities are going to be determined or prioritized?**

Recent interest has been expressed from a company but they haven't said which process or material. We hope to have more information soon. It's definitely on the roadmap for this committee. There are applications that require those material properties so we will be working to develop standards for ceramics. I envision that to be either binder jetting or maybe some fused filament fabrication (FFF) or other AM processes.

**How are manufacturing organizations engaging the use of AM and how do you see the need for further standardization adoption?**

The industry as a whole is very engaged. We have over 550 members, from Tier 1 manufacturers, equipment suppliers, material suppliers, and service providers. There is also a lot of engagement from agencies such as NASA, FAA, DOD, Air Force, Navy, Army, etc. We're seeing more parts in commercial applications and on the defense side.

**What is the situation with so-called composite FFF/fused deposition modeling (FDM) additive manufacturing?**

That is one of the processes that falls under the non-metallics subcommittee. I'm assuming that the question is asking about those filaments that have fiber reinforcement. So those are also on the roadmap. It's my understanding that we do not have a technical sponsor right now but if the person who submitted the question has experience we would very much welcome his or her engagement with the committee for non-metallics to help with that development.

**How does one access specifications?**

These are public specifications. You can go to the website for AMS or your company may also have membership with a re-seller such as IHS for accessing industry specifications. You can also search online by the specification number. SAE Standards Works lists all the specifications that have been published or that are in development for additive.

**Given your role and in terms of technology development, what factors make a standard a favorable opportunity for an SDO to address?**

It's definitely demand. During a meeting in 2015, there was no specification or standard for Inconel 625. The committee voted for Inconel 625 and laser powder bed fusion (PBF) to be the first set of specifications that needed to be developed. So AMS 7000 through 7003 were the first ones worked on and developed over the course of 2 ½ - 3 years. After that, we established the framework and the templates needed to develop specifications for additional materials and processes. So now we have wire-fed processes, powder-fed processes: laser and electron beam directed energy deposition (DED), laser-beam PBF (PBF-L), electron beam PBF (PBF-EB). All the relevant processes are covered in the committee and there's more coming like the one that was asked about earlier. The work is volunteer based and we appreciate the time and devotion that the members put into working the specs through the different ballots, addressing comments, etc. It takes between 12 to 24 months to have a spec published.

**Shane Collins, Head of Additive Manufacturing Advisory Services, ASTM International Additive Manufacturing Center of Excellence (AMCOE) [Presentation Link](#)**

Shane Collins gave a presentation on ASTM F42 in his capacity as head of ASTM's AM advisory services and chair of F42.07, applications, having previously served as chair of F42.05, materials and processes. F42 has been writing standards for AM since it was established in 2009. It is divided into subcommittees on test methods, design, materials and processes, health and safety, applications, terminology, U.S. TAG to ISO/TC 261, and data. The committee has over 1,000 members from 35 countries with 30 published standards and another 45 in development. Standards are developed in partnership with ISO/TC 261 and co-branded with the logos of both organizations. Other ASTM committees that bring a lot of background to work on AM include E07 on nondestructive testing and F04 on medical devices.

There has been an evolution in how the committee views AM part qualification. With metal AM in particular there are anomalies, such that the business case has to be considered along with part criticality, technology maturity, the certification path, and so on. In analyzing whether AM produced parts are safe, it is a more acceptable strategy to look at whether they are defect tolerant rather than defect free. We analyze based on fracture mechanics and fatigue crack growth, and inspect to what is applicable for the application. Part qualification can only evolve with a robust part classification system. There is a work item, WK77559, based on an analysis that was done of all the part classifications that exist in different material guidance for aviation. Another work item is WK70164 which will be a practice for assigning part classifications for additive manufacturing parts used in aviation.

In the area powder bed fusion, F42 is looking holistically at the specifications needed to have a known part capability. This includes feedstock and materials specifications, design allowables and mechanical properties, design for additive manufacturing, requirements for part classification, and equipment and factory testing. ISO/ASTM 52941 deals with factory acceptance testing, shipping, machine calibration, site acceptance, qualification, and calibration. There is also a standard, ISO/ASTM 52930, related to machine metallurgical qualification, and ASTM F3434, governing installation, operation, and performance qualification (IQ, OQ, and PQ) of PBF-L equipment for production. ASTM and ISO have process mapping for metal PBF and DED.

ISO/ASTM 52941 deals with system performance and reliability, acceptance tests for laser metal powder bed fusion machines for metallic materials for aerospace applications. The standard ensures that equipment has a fitness level to meet demanding, critical applications. It provides a means for an operator to stay within the various attributes that create a process window. Some of the other key standards for critical applications such as aerospace, medical, oil and gas, and automotive include: ISO/ASTM 52901, a guide for AM general principles required for purchased parts; ISO/ASTM 52904, which sets requirements for a metal PBF process to meet critical applications; ISO/ASTM 52942, on training for machine operators of PBF-L machines in aerospace applications; and ASTM F3434 noted earlier.

Key standards in development include: WK72172, a new practice for AM data pedigree and a common data dictionary; WK62190, feedstock materials technical specifications on metal powder; WK66030, a guide for

quality assessment of metal powder feedstock characterization data for AM; WK75901, test artifacts for tension testing of metals; WK62181, a guide for in-situ monitoring of metal AM aerospace parts; and WK75329, Nondestructive testing (NDT), part quality, and acceptability levels for AM PBF-L aerospace components. These standards are filling the need for the feedstock, and the whole process of testing and backend NDT requirements.

Some other interesting work items are: WK77186, a standard for niobium-hafnium alloy. There's a big push to go into ceramics but there are a lot of metal refractory alloys that potentially could fill that gap that are produced by PBF. This particular standard would enable printing for very high temperature applications where normally you would use ceramics. A more general purpose alloy specification is WK66637 for low carbon steel that is a very high strength material. It will be used for heavy construction equipment, automotive, trains, and other transportation applications. Lastly, WK74302 is a standard being developed for residential construction, an area that ASTM is heavily focused on.

### **Q&A**

**Have you seen any sort of commonalities in terms of feedstock materials standards? People are generally familiar with the attributes for metal powder, in terms of things like chemistry, size, shape, and distribution. What are you seeing in terms of other materials? Are the features similar or unique?**

If you look at the history of AM, you had stereolithography and the resins used for the photo ultraviolet (UV) curing which were supplied by the machine manufacturer. Then, you had selective laser sintering and nylon powders. The distribution of those were held closely to a couple of companies. When metals came out, the machine manufacturers tried to keep the same business model of supplying the powders, but the powder metallurgy industry had been in existence for a long time so that took a different path. Metal powders are a commodity but there's an opportunity for more widely adopted practices to bring those to market. Metal powder is shipped in small plastic containers though tons of powder is needed for some of the larger machines. So batch variability is a concern along with lot control and testing. The same thing can be said on the polymer side for the filaments for different material extrusion systems. Those materials were largely proprietary to the machine manufacturers. But when the maker movement started to proliferate those types of printers, different materials came out and now there are a variety of material suppliers. As feedstock materials for additive systems become commoditized, there will be a need for compliance to more strict standards.

**Is there any plan to review or update the specifications on titanium powder, ASTM F2924 and F3001?**

The first draft of F2924 was written in 2012, then updated in 2014, within F42.05. These standards have come up against the deadline where ASTM requires them to be reviewed. They are currently being balloted as originally passed. WK77168 is an updated version of F2924. F3055 and F3056 will also be updated with a couple of different applications in mind. It will probably happen that there will be titanium specifications specifically for medical implants. There could be other applications as well, with more alloys being developed for AM that currently are not used widely.

**How will standards evolve as the digital tools and artificial intelligence (AI) activities for AM go from descriptive and diagnostic to predictive and prescriptive enabling closed loop?**

There's still some way to go to make it a completely closed loop system. This is the Holy Grail: if we could find a system that would predict defect and then modify the energy density or some other parameter to make sure that the defect doesn't occur in the material. That would be the ultimate AM tool and then we could eventually stop using any post-processing nondestructive evaluation (NDE) because we would know that the material is defect free. There are some low hanging fruit that we can be looking at now that are maybe not melt pool monitoring per se but process monitoring. Particularly, in PBF we find that anomalies in the powder spread layer usually turn out to be not good in the material. Defects can occur when you short feed, or when there is something wrong with the powder spreading. It wouldn't take that much AI capability to look at what a good powder spread is, compare that to an existing layer, and at least flag whether or not there is a possibility for making a determination that a layer needs to be looked at more closely later on. It's going to be an interesting time. At one of our recent quality meeting seminars, we had a gentleman that's looking at closed loop control for a material extrusion nozzle and that's going to be exciting as well. So that if you are looking at possible

defects to occur, possibly because of a change in the diameter of the filament, you could adjust the heat on the fly or some aspect to the nozzle to create a more defect free part. All of that is coming and it's going to be an exciting time for additive.

**Cindy Ashforth, Senior Technical Specialist, Federal Aviation Administration (FAA), and Composite Materials Handbook-17 (CMH-17). [Presentation Link](#)**

Cindy Ashforth provided remarks covering FAA requirements for material control, CMH-17 activities (in her capacity as co-chair), and composite and AM material control methods. From a regulatory perspective, material and process definition is part of the design of an airplane, engine, or propeller and is approved and certified the same as any other design feature. There is not a way to certify independently of a product or a part. There are some general requirements to adequately define the design such that you can be sure that it always meets other requirements for strength or performance. There are specific rules for the various products that focus on material control, process control, and design values.

There are three items to define and control. Only one of them is governed by regulation – the final part material. The regulations require that the final material be controlled. That is done by defining and controlling the feedstock material and the process used to convert it to a part. Within composites, there are other materials besides laminate such as core, adhesive, and non-flyaway materials that have to be controlled to some degree. Within AM, this includes reuse methods but may also include the build plate and other support materials. These things influence the final material that is the part and require a level of control. The degree of rigor applied to these controls can be commensurate with the criticality of the application, which means it's not one size fits all when it comes to aviation.

The importance of adequate material and process control cannot be overstated. You cannot certify a product if it is not being produced in a stable manner. And that requires a stable uncured/feedstock material. A building block approach may be used to generate empirical design data at various structural configurations rather than trying to use data from a very simple configuration to predict behavior of a full-scale structure. Stable materials are the foundation for successful applications with advanced materials and processes such as composites or additive manufacturing. When you have material data, equivalency testing is required to buy into a published database. That's what's been done for composites and where things appear to be headed for additive.

OMB Circular A-119 requires all federal agencies to use voluntary consensus standards in lieu of government unique standards for regulatory activities. If they don't, they must notify the Office of Management and Budget (OMB) that they are creating a government unique standard in lieu of a voluntary consensus standard. FAA regulations, guidance, and policies are supposed to be performance-based, so they don't get to provide a lot of detail. The take-away is that minimal FAA guidance is forthcoming and FAA relies on industry standards.

The CMH-17 handbook has evolved over time from what was originally several military handbooks and now includes a brand new handbook on additive manufacturing. The handbook has three goals. The first is to provide material data such as physical and mechanical properties. When these values are published, they are tied to a single material specification and a single process specification which are published elsewhere. CMH-17 does not publish any material standards. The second goal is to provide information on how to generate material data. This is where there are best practices and requirements for material and process control, test matrices, and statistical methods used to put data into the handbook. Each material can have two or more statistical databases, depending on how it was processed. Most of the content within CMH-17 – and this is the third goal – is on how to use the data. It is a design guide that's based on proven methods and best practices and includes information on manufacturing and maintenance, relying heavily on industry standards. To summarize, the handbook does not publish specifications, but it does have guidelines on what information should be included in specifications, minimum requirements for material data submission, and best practices for use of composites and non-metallic AM materials.

Ms. Ashforth provided a detailed explanation of the differences in how specifications are structured for composites versus AM. With composites, a single material specification covers both the raw or uncured

feedstock material and the processed material. In AM, the feedstock typically is controlled in a different specification than the finished/printed material. From a regulatory standpoint, any specification structure is acceptable as long as it controls the required information. Methods of controlling material reuse are not yet standardized. One method could be to reuse powder within a single lot. CMH-17 encourages industry standard organizations to develop feedstock material standards that support end state material controls. CMH-17 is developing a new volume that will include best practice guidelines and data for controlled materials and processes.

#### **Q&A**

##### **Any considerations or guidance regarding the statistical significance of material data generated?**

There's a regulation that is required for design values and structural strength in aircraft products. It's a 9095 B basis or a 9995 for A basis, depending on whether you have redundant or single path load.

##### **Do you believe there's an opportunity to commoditize composite feedstock for AM processes?**

I'm not entirely sure what you mean by a composite feedstock for AM. In general, yes, I believe there's an opportunity to commoditize feedstock, whether it's a polymer, metal, reinforced or unreinforced. Something I'd personally like to see commoditized are reused composite materials. When we recycle composites and chip the carbon into flakes, that's an opportunity for creating a new material standard that could be much more of a commodity than we see in traditional pre-preg materials.

##### **What sort of research or data would be necessary to make that happen?**

We could do it at just the reinforcement level very easily. It takes industry need. Someone has to need it, want it, and be willing to do it. In the Seattle area, we have several state funded activities working on composite recycling to see how to chip the pre-preg materials and then reform them into a new material for composite pieces. It's probably not for aviation but for other industries. If you wanted to use it in aviation, some of the non-structural ones. For a composite to truly be a commodity, you're going to have to give up a resin formula. And you're going to have to say, the same way that we give up chemistry on metals, this is a commodity, and everyone can compete in making it and providing it in an inexpensive manner. That is a potential but it hasn't happened until now probably for a reason. There's probably no business case, but it could happen theoretically speaking.

##### **Teresa Melfi, Technical Fellow, The Lincoln Electric Company [Presentation Link](#)**

Teresa Melfi gave a presentation about a small subset of feedstocks: metals and wires. She did so in her capacity as chair of the American Welding Society (AWS) filler metal standards committee, that has liaison between ISO/TC 44 and ISO/TC 261, and representing Lincoln Electric, a producer of wire feedstock that also manufactures parts from these feedstocks. She provided historical context of the elements that go into a system and how they fit together in a way that works well for users, producers, insurance companies, and regulators in the welding and additive spaces.

AWS is over 100 years old and there have been consumable specifications in place for almost as long. There are billions of pounds of weld metal deposited every year. Shape welding or weld buildup parts have been used in highly critical areas such as nuclear power plants, bridges, off shore rigs, and pipelines, for many decades. The specifications are updated regularly because things change.

In terms of procurement guidelines, AWS A5.01M/A5.01 is identical to ASME II-C SFA-5.01 and nearly identical to ISO14344. The three of them together are the most widely used methods for procuring metal wires for welding. In terms of what's in the specification, there's a scope, normative references, terms and definitions, but the two most important things are the lot class and the level of testing. The scope "identifies various information necessary for communication between a purchaser and a supplier of welding or brazing consumables." The way you do that is to reference a filler metal specification and those are grouped by alloy types. Then, you specify the lot classification and the testing schedule. These two are determined based on the criticality of the component and the use of the final product.

There are four classifications for a fully metallic solid consumable. Lot Class S2 is used in the most critical of applications. Once you define that classification, you specify what tests you want done. The most commonly used test schedule is schedule 3 or H which is the chemical analysis of the specific lot. A5.01 also has some annexes including a mandatory annex that details quality assurance requirements of the supplier. A typical purchase order will specify the wire diameter, classification, lot class, and testing schedule. In addition, most consumable suppliers stock products to various lot class and testing requirements. When a manufacturer puts the AWS specification and classification designations on the packaging, they are certifying that the product meets the requirements of the specification.

#### **Q&A**

#### **Are there lessons learned that the metal wire feedstock community can share with the broader AM community for other standards development efforts in polymer filament or fibers for reinforced composite structures?**

The biggest lesson learned is that it's good to break things up rather than trying to have one big specification that covers the details behind the material properties and the procurement. It's good to have one specification that describes one part of things and another that describes another. It makes it simpler for people to use.

#### **Kate Hyam, Director of Nuclear Codes and Standards, American Society of Mechanical Engineers (ASME) Presentation Link**

Kate Hyam explained that ASME is a large international organization that develops standards and has certification and conformity assessment activities. ASME offers learning and development courses including a series of courses related to additive manufacturing. It also has a series of conferences and is seeing more and more papers related to AM in all of its conferences across all industries. ASME's publications wing develops press books. ASME.org has many useful articles and resources available. ASME's education department works with the academic community on curriculum and accreditation, and on workforce readiness providing K-12 students with STEM opportunities. ASME is a large membership organization with divisions and industry affiliation groups. Some of them are materials related. Many of them are looking at additive manufacturing. Lastly, AMSE has an industry events department that provides many AM industry summits, including an upcoming one on aerospace, and automotive in August, as well as medical and energy.

ASME is an international developer of standards and has been developing standards since 1880. It has approximately 600 standards that are accepted for use in more than 100 countries, 70 consensus committees, and 700 total committees operating under 5 supervisory boards. It has close to 6,000 volunteers, 800 of whom are international, and that number is growing, as well as 12 conformity assessment programs.

Related to additive manufacturing, ASME has a number of standards in development. Y14.5, on dimensioning and tolerancing, has been the drawing standard engineers around the world have used for decades. Expanding on that base, additional standards were added to the portfolio to support AM and model-based design standards. Y14.37-2019 establishes the definitions as well as exceptions and additional requirements of composite parts. Y14.41-2019 establishes requirements for digital product definition data, such as data sets or graphic sheets in digital format. Y14.46-2017 establishes definitions of terms and features unique to AM. It provides a method of controlling product definition directly in the model using annotations that are human and machine readable. It leverages model-based product definitions for AM, includes definition of 3D geometry for the end item and also for process control, provides data package bundling details for AM, and assists in specifying the geometric placement of material and material gradients. Y14.47-2019 standardizes the exchange of 3D model data used to define an item for manufacturing and procurement. Y14.48 is in development and it will address build direction in additively manufactured parts, direction of fibers in composite parts, direction of geometric tolerance zones, direction of surface texture requirements, and other specifications.

ASME has a number of additional standards activities related to additive manufacturing. B46.1-2019, on surface texture, was published about a year ago. Appendix B has sections on AM terminology and characterization best practices, noting that AM surface as built could be sufficient and not need post-processing, with acceptability parameters for those types of AM parts. It includes cautionary statements on limited knowledge base and a

wide range of AM systems and materials. Appendix K includes suggested terminology and procedures for the evaluation of functional correlations of surface textures with processing and performance. There is an active project team on surface textures for additively manufactured parts that is continuing to expand B46. B89.4.23-2020 specifies the dimensional measurement accuracy of industrial X-ray computed tomography (CT) systems. The Board on Pressure Technology and Nuclear Codes and Standards has just issued pressure technology book PTB-13-2021, Criteria for Pressure Retaining Metallic Components Using AM, specifically for laser and electron beam PBF, and this will be expanded in the future. There is a bioprinters committee which is developing standards for bioprinter hardware requirements. The model-based enterprise (MBE) committee is addressing the need to replace existing business models of document-based processes and workflows with data-based processes and workflows. These activities are aimed at enabling the digital thread across a product life cycle and are key for AM data management. The verification, validation, and uncertainty quantification (VVUQ) for computational modelling and simulation committee is developing a standard on computational model life cycle (CMLC) in advanced manufacturing production systems which will be applicable to AM.

ASME's newest applicable activity approved in December 2020 under the manufacturing and advanced manufacturing standards committee is a subcommittee on AM. Working groups targeted to start later this year include a design for metal AM workflow practices working group, and a documentation requirements to meet government and regulatory certification criteria working group. An AM for non-metallic materials applications working group under this subcommittee held its first meeting in April 2021 and has been meeting monthly with the next meeting this afternoon immediately following this event. Thus far it has been mostly brainstorming with speakers like Brandon Ribic and Matthew DiPrima discussing the AMSC gap analysis and opportunities in medical. The group is reviewing existing standards to reference them and to avoid overlap. A few project teams have formed and are at a preliminary stage of work. Items that have come up include: feedstock material selection and qualification (biocompatibility), supply chain control, using material science to help engineer the part and replacement of metallic parts using non-metallic materials. There are a number of other ASME committees that will most likely will eventually incorporate the use of additively manufactured parts.

#### **Q&A**

**Is size of the item being printed defined in Y14.46, and what defines "large-scale printing"?**

I don't recall that being defined in there. We have online Fred Constantino who is responsible for Y14.46. So, Fred, if you have an answer to that, could you put it into the chat.

**The U.S. Nuclear Regulatory Commission (NRC) held a discussion last year around AM for nuclear. What special considerations foster standards development for those applications? We've heard today so far how demand and application influence standards development. Are there matters which the precursor and feedstock materials community needs to be cognizant of supporting future production opportunities in AM for nuclear applications?**

Teresa Melfi has noted in the chat that the boiler and pressure vessel (BPV) section III (requirements for nuclear component parts) is working to have rules for AM in the 2023 editions. I don't know exactly what will be in it, but they're going to have to start addressing AM in that edition. Isabella Van Rooyen is going to be on the panel discussion this afternoon – she is also on our non-metallic materials working group – and she might be able to answer that a bit more completely. With nuclear, you need to know every stage of the production process. It has to be documented very clearly and it is incredibly important for NRC compliance.

**Medical components shown in the public literature often feature cellular or lattice structures. Are there special considerations to define the necessary attributes, feedstocks, or precursor materials utilized in those medical applications?**

The main concern for those medical applications is biocompatibility. When you're replacing tissues and other components, you have to be able to match functionality of your bioequivalent component. I believe that will be very important.



**As noted, the BPV III executive committee has a goal to have rules for AM in the 2023 edition. Do you feel the timeframe is possible?**

Yes. I think we'll have something in the 2023 edition based on criteria in a document published last month.

**What are the hardware requirements for printing bio materials?**

That is currently the focus and function of our bioprinter standards committee that was formed not more than a year ago. That's what they're attempting to identify and put in that standard.

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Mr. McCabe thanked the morning's presenters for their contributions, noting the presentations will be made available. He invited participants to reach out to speakers with any further questions.

**Session 2: Panel Discussion on AM Feedstock Materials Considerations**

**Moderator: Brandon Ribic, Ph.D., Technology Director, America Makes**

Brandon Ribic introduced the speakers and invited each to make opening remarks. They then answered some prepared questions as well as those submitted by audience members. **(Note: throughout this report, speaker remarks are abbreviated and summarized to note key points.)**

**Opening Remarks**

**Bryan McEnerney, Ph.D., Group Supervisor, Materials & Processes, National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL)**

At NASA Jet Propulsion Laboratory our charter is robotic exploration of the universe. We work within the broader NASA charter. We have swim lanes for all the different centers. JPL is not focused on crewed spaceflight as much as it is in an auxiliary support role to both our industry partners and the other NASA centers. Our focus is primarily on feedstock for advanced materials. We focus on gradient alloys or specialty materials that are needed for our mission as well as acquisition of materials for some of our gross structural applications that are going to be more commonly available. I was part of the committee that drafted NASA standard 6030, which is the comprehensive document for how to qualify any material in any process for spaceflight. And I served on both the crewed committee and was chairing the non-crewed committee.

**Igor Levin, Sc.D., Leader, Materials Structure & Data Group, Materials Measurement Science Division, National Institute of Standards and Technology (NIST)**

NIST has been very active in metals and polymers. We started a project a year ago on additive for ceramics. Prior to the pandemic, we organized a workshop on ceramics AM dedicated to research and measurement needs. It was attended by a number of equipment and materials manufacturers, companies that do on demand printing and also some of the end users. There were a number of recommendations from this workshop which you can download in the report that we published in the journal of the American Ceramic Society.

**Isabella Van Rooyen, Ph.D., National Technical Director, Advanced Methods for Manufacturing Program, Idaho National Laboratory (INL)**

At Idaho National Laboratory, I am a distinguished staff scientist as well as the national technical director for U.S. Department of Energy (DOE) nuclear engineering advanced methods for manufacturing. INL and the nuclear energy industry are interested in metallics, ceramics, and composite materials. Our research has focused on exotic materials. Recently, the new funding, vision, and mission of the DOE nuclear engineering is to put forward deployment of advanced reactors. The focus is on researchers and developers in earlier development stages to think about how you are going to qualify this. My interest is to understand what is in the interest of the nuclear industry and other industries.

**Teresa Melfi, Technical Fellow, The Lincoln Electric Company**

In general, what I'm doing with additive and standardization is picking the low hanging fruit for nearly immediate use in different areas. This includes ASME section III nuclear work to try to get some of the components recognized as well as piping and pressure vessel codes. We have a new code case out for section IX

for process qualification. We're also working with the American Petroleum Institute (API) and some of the other construction standards. My area is very much the established methods of powder and wire base for immediate use in components and critical applications.

**Bill Bihlman, Ph.D., Founder & President, Aerolytics LLC (SAE International)**

I'm representing SAE international. Hector Sandoval did an excellent job this morning talking about our focuses. Just to reiterate, SAE started in aerospace material specifications (AMS) back in the nineteen thirties with our first publication in 1939. So really this is a continuation of a lot of the metals work that we've done and then moving into polymers. Our focus are the core commodities to aerospace: titanium, super alloys, aluminum, high strength steels, and then also polymers (e.g., PEI), and eventually ceramics.

**Eliana Fu, Ph.D., Industry Manager: Aerospace & Medical, TRUMPF**

My background is material science. I'm very interested in metals, especially things like titanium. I've been working in AM for the last seven or eight years, starting with TIMET and then SpaceX. One of the most memorable moments that I had at SpaceX was to do a North American review of powder manufacturers for AM with other engineers. Since then I've been interested in supply chain and materials. With Relativity Space, my former employer, I also looked at additive processes. When it comes to materials and processes, you can't have materials without the process, or the process without materials. I'm really fascinated by feedstock considerations. I worked at TIMET, a big producer of titanium in the U.S., for eight years. No one has really moved past the Kroll process of making titanium from its ore for over seventy years. That's kind of an interesting conversation for me.

**Shane Collins, Head of Additive Manufacturing Advisory Services, ASTM International Additive Manufacturing Center of Excellence (AMCOE)**

I introduced myself during the presentation earlier so I won't repeat that but there was an interesting question in the chat on how do you position ASTM standards versus AMS ones. I would assume that they are talking about SAE more broadly and not just AMS. That's a very interesting question and I think the next few years will determine how that comes out. From a pragmatic standpoint and as a user of the standards, it's very important that we limit the duplication of efforts as much as possible. On the different work items that I'm involved with, oftentimes it's a lot of the same people who are involved in SAE, ASTM, and ASME. A limited number of folks are doing a lot of the heavy lifting for standards development. And when you go to conferences and meetings, you see the same faces over again. So, I'm really happy for some of that aspect, but because we have a very limited number of people, it's important that we try to not duplicate our efforts.

**Moderated Discussion**

Mr. Ribic kicked off the discussion noting he'd like to see the conversation cover fundamental considerations, then look at it more holistically from a supply chain perspective, and touch on the future development of standards and what more can we be doing.

**Many folks first pursued proprietary specification development due to time constraints or their strategic agendas that they're not going to publicly disseminate. Thinking beyond metals, do feedstock and precursor materials lend themselves to standardization? And does this vary by industry or material type?**

(Bryan) I think it is actually important to have a great deal of standardization. My formal training and a lot of my research is in ceramics. One of the challenges with ceramics is that you don't have an ASTM standard, or an AMS, ANSI, or other standard the way you would for a metallic alloy system. We see the same issue with polymeric. I can't speak for all applications but in our application we found that when you have that sort of lack of a coherent baseline for these materials you can have a wide range of variability and that has unintended consequences. Some of the other panelists have worked in aerospace or what I'll call high fidelity applications be it nuclear or otherwise. You cannot have those kinds of high cost to failure issues crop up. My feeling is you need to have a higher degree of standardization or at least maybe a common baseline for minimum things. They need to be reported or understood for a lot of these materials. We've seen it time and again with polymers and ceramics. It's also not just an issue for additive but for traditional materials.

(Bill) Speaking on behalf of aerospace, I think standards clearly are important. The whole idea is to drive costs down. But what's interesting is the variation in chemistry. For example, with regards to titanium 64, probably the most ubiquitous material, there's variations in the percentage plus or minus 1%. So there are variations in the chemistry but to a certain extent it's control. If it's too tightly controlled, that drives the cost up. In additive manufacturing, because of the low TRL, it's really understanding those process windows, both from the chemistry side as well as in processing oxygen pick up, carbon pickup, and so forth. To the second question, I do think there are some fundamental differences in the industries. One of the things that we address in aerospace is the high cost of failure. When you certify an article, you certify that bill of materials. There's a danger at using proprietary materials whether it's alloys or non-metals insofar as you can run into problems with sourcing. We're talking long product life cycles, upwards of thirty years, so that needs to be considered. It's how are you going to maintain that product and the accessibility to those materials that takes you away from using intellectual property or materials that are considered proprietary.

**It seems like a barrier to entry to developing a standard tends to be due to regulatory requirements around certain types of applications. Would you all agree that those tend to be the industries or markets that lend themselves most to standardization in the early phases of technology? Or is it things like automotive where the volumes are incredibly high where we also need standardization. Are there variables in terms of volume? Or is it always criticality and regulation that drives this?**

(Isabella) The nuclear industry would like to show the performance of new advanced reactors and deploy them. We want to produce components and parts using additive manufacturing processes or other advanced manufacturing processes quickly through a standardized process for reliability and reduced risk. The environment is different from other industries but we want to learn from other industries.

(Shane) If you look at the number of additive parts that are produced on an annual basis, there are many more polymer parts produced than metal parts. A few years ago, an attendee at one of our F42 meetings was making an automotive light lens cover. The complaint was that "water clear" is not water clear to all the resin manufacturers: some is kind of yellowish, some is sort of clear, some is foggy. Here's a perfect example where standardization can play a role not only in the highly regulated industries of automotive and nuclear but even in the prototype phase or when we are in product development. The standards would be extremely important.

**In the world of thermoset chemistry, oftentimes it's final part performance that is specified. Are material specs as critical in the AM process? What is the balance between specifying things around the feedstock material? Or is it more critical that we consider the material and the process as a package?**

(Teresa) In the world of weld metals, your feedstock and your weld metals will often have different chemical compositions because of the losses that take place. I'd have to say both. It's important to specify in fairly great detail the finished product composition and the finished product performance. But without specifying the same things for the feedstock, I don't think you can get there reliably and comfortably. In those areas where we don't have good specifications for feedstock, it really has to come from the designer.

**So, fit for purpose is still very important with feedstock attributes, design specifications, etc.?**

(Igor) I think the same applies to ceramics because you usually end up with a green part, which has to go through sintering. Sintering is going to be affected by your feedstock. It still has to come as a package, depending on what you want to do with the final part.

**Along those lines, and based upon the additive manufacturing technologies in use today, are there special considerations that the community needs to be more cognizant of in order to appropriately specify a feedstock for a given application? What can you share with us in terms of lessons learned?**

(Igor) With ceramics, there are different kinds of feedstocks. Depending on the kind of technique, there are pretty much three major types of feedstock with different requirements. It's not just the powder for powder bed, but powder for the binder. It's really a combination that determines the final performance. At the moment, there is no clear understanding of how existing standards actually apply to ceramics. Some of them do and some of them may need to be modified.

(Isabella) There was a question “What if feedstock is itself a blend of components? We often have that in our type of processes. Controlling the process is important from the beginning stages. Developing a robust process where you can get repeatability while keeping uncertainty low.

(Bill) The reference was back to Cindy's presentation and she provided a slide. It's pretty common with the FAA – it's called the building block approach. You define the material, the process, and kind of the consolidated materials and the materials property database. This is where you get the design allowable. This hierarchy or pyramid is the base and that's where we have those test coupons. So, the process is as critical as the material. Process control means controlling the process and the material that equals the final part. The standards debate is around the level of specificity and how prescriptive do these standards have to be. Do we provide just the list of ingredients, or the actual work steps and the formula to get to a specific part? The latter has been the course of composites historically although the material compositions may be proprietary. That's how companies protect their intellectual property. But that's how the FAA and EASA approach it with that building block approach. So, again, material is just as important as process. And that's what defines the final part.

**We heard Igor and Isabella talk about processes that are not powder bed fusion, or directed energy deposition. Those are not always utilized for polymers or composites. Do you think there's opportunity to standardize precursor or feedstock materials to address the needs of other AM processes?**

(Bryan) I think you need to look at the end to end process route you're taking. If you look at ceramics, in particular, truth oxide ceramics, most people think of them as fairly stable because they're not going to oxidize. But if you have moisture content, you're going to form a hydrate on the surface, which can become tenacious. And when you go to densify the part, you might not be able to eliminate it. Much as you'd concern a metallic system with oxide scale for reuse of powder, I think you need to look at not just the form you have but really look end to end and what your detailed process flow might be. If you're trying to create a porous catalytic bed to infuse your catalytic agents, one processing approach might work. But, to some extent, you would have to look at the totality of what your end application is coupled to what process you're taking. Because I could give you a beautiful aluminum oxide specification with chemistry and particle size, but if it's powder bed fusion versus a paste or slurry extrusion, I'd have to very much care about solvent or secondary binders and any reaction. At least with oxide materials, you don't worry about oxidation. But when you start getting into your non-oxide, you also have to worry if you have binder materials are they going to be carbon rich and lead to propensity for formation of carbides which may be undesirable. Or even if you have an oxide, you can get a carbothermal reduction and have a chemistry variation. So, I think you have to look at all of that and map it the way we tend to. We tend to focus on laser powder bed fusion or electron beam powder bed fusion. But the same question applies to metal if you're looking, for example, at the e-beam wire feed approach. You need to think about your feedstock and your end microstructure and how you're going to heat treat that in a very different way than you would a part. Because you could be putting a bracket or other type of feature onto a large forging that already exists and you don't want to screw up the whole forging. I think you need to break it down into work streams and look at the different forms and think about what you may want to adjust in that kind of approach.

(Isabella) We do process development with the scientific view that we will be able to transfer that process into our more controlled environments going forward. As a community, we can learn from other industries and then translate it back to our processes.

(Eliana) I was going to offer another point of view on wire. When I was at Relativity Space, we used the wire arc additive manufacturing (WAAM) process. One of the things I noticed is that some of the wire suppliers just make wire for welding. Then they find out that you want to actually build structures using AM. At the time, I felt like there could have been a lot more support from the supplier or the manufacturer, recognizing that what may be a fraction of the business now is going to grow. So, I'd like to see more of what can we do to help you?

(Shane) Or we could just have a standard and then make the wire suppliers comply with it. That would be another avenue.

**I think you both have a great point. How do folks juggle a stacking set of requirements versus being an effective supplier being able to begat a profit making model? I think you're on the right path, Ellie, talking about collaboration and not acting out there on your own. How are we communicating considerations that go into effectively sourcing feedstocks? Are people doing that? Are we learning together?**

(Eliana) I would love to see more participation on these kind of panels from actual material suppliers because I do think they are interested and they do see that as a growing business sector. But I don't see them saying we're going to put all this effort into AM. Traditional business is still going on. If you talk about titanium for aero engines, it is probably 75% of their business. And AM is a fraction of it because those parts aren't flying right now. But in the future they will be, when we have standards. The mindset needs to transition from it's just a commodity that we sell and it's on you the customer to figure it out. I don't want to be that customer asking what can I do with this material, how can I make it better in my process, whether it's a WAAM processor, a DED processor, or powder bed.

(Teresa) I appreciate that. I think there's two sides to it. We sometimes laugh when when we look at filler metal suppliers that make specific wires for additive, and brand these specifically for additive, and charge a higher price for them because it's for additive. A commodity wire to me is one that meets the very basics of the specification and the chemical composition and things like that. But if you look at the type of wires that go into some of the robotic applications, those are produced to a much tighter standard than most of the wire going into the additive applications. And that's because of the placement and such is so precise. It's going to certainly be easier to source those if you're using for traditional alloys. When you're using Ti that's going into very specific areas and it's not the kind of supplier that understands what has to be done to precisely place wire each time. I think in some of those cases there is communication with the supplier that has to take place to learn how to do those things and maybe they're not capable. Maybe there is a secondary step in there to properly twist and place a cast and pitch on the wire so that it does place appropriately and has the appropriate surface finish to it.

(Shane) I would add that it's pretty normal for additive manufacturing to require a slightly different chemical composition, or a different aspect to the feedstock than what you would use off the shelf for other applications. On Ti64, Puris was making a fortified version with higher iron content within spec, but high aluminum because they knew with electron beam, for example, aluminum would get burned off. Maybe doing arc welding with aluminum the wire may have to have a special formulation to make 3D objects without flaws. That's a pretty common aspect. I go back to the America Makes program with polymers where we were adding chopped fibers to modify the material properties as well as the electrical properties. It sure would have been nice to have a standard back then as to what are the size of the fibers. Would nano fibers work better than the micron version? What would be the composition of the fibers? How are they made? How do you dry blend? How do you make sure you get a homogeneous? How do you recycle that type of material? All of that would have been really nice to have as a guideline. But we were sort of making new ground. I think a lot of additive programs are in that area of you're trying to take off the shelf product but it doesn't quite fit in the box. So you have to make some modifications which leads you down a science experiment which loops you back into wanting to have special material requirements. It's a nice loop that we tend to get stuck in. But hopefully we get out of that and standards can help make it happen.

**Thank you, Shane. I think that's a great point. There's a question here from the audience: How can we better articulate our requirements as a community to ensure that we are better supported by the existing or traditional supply chains?**

(Teresa) I think everything that's done in this space, rather than being a one-sided science experiment, has to be collaborative. Because everybody understands a little bit differently what properties make the aspect of a material what it is, whether it's physical or chemical properties. The communication and collaboration side is really key. It has to come before any standards are written so that we understand what we need to get standardized.

(Eliana) I've just seen a comment. It kind of echoes what you said, Teresa. I think the key is to talk to people but also to listen to people, especially customers. When I worked at Relativity Space, it was working faster than most people are traditionally comfortable. You have an idea and you need material right away. But for the

supplier there's a lead time to actually make it. So that's another disconnect between the person doing the designing or the person wanting to build the part, the manufacturing engineer, and the supplier. The flow of communication needs to take place. But it's also not just one side always communicating. The other side really has to listen.

(Bill) It's interesting when we have these panel discussions. We get all excited but, at the end of the day, there has to be a business case. The standards need to be relevant. We don't want to write a standard for the author. In SAE we have a diverse group of participants. We are OEM-centric because they have deep pockets and they're driving the design and that informs the supply chain. But really the standards are being written for the supply chain. The OEMs more or less have their own internal standards. We look at the demand and say that we need two or three existing customers to write the standard. We don't want to write a standard for a particular product that's more or less proprietary. We've had companies approach us to do more or less that. So it's kind of a balancing act. The voice of the customer is important but, if the market doesn't exist . . . we have to realize that this is a relatively low technology readiness level (TRL). On average, additive is on a level three, four, or five TRL. For that reason, a lot of this information isn't disseminated, so it's not a commodity. What we're trying to do is to help move that forward to industrialization. It's important but it also has to make business sense from each enterprise's position.

**Along those lines, if we look at polymer – and we can include chopped fiber – I want to understand why aren't there more standards around polymer, even filament feedstocks or pelletized feedstocks where there are publications and a lot of data out there? Then we have lower TRL technologies where people are starting to explore continuous fiber reinforced polymer matrix structures. Maybe they're not the right TRL level, but what about those? Why is there not a need? Is it just that the applications don't begat a demand for those standards?**

(Bryan) I think it's because a lot of your development is non-structured. At the lower TRLs, you're beginning to kind of organically create a process and come up with something. By the time you start having customers come in, you don't have a structured way to drive that format, or those requirements. If you look at NASA, we have a bunch of hyper formalized requirements and different pieces of knowledge gained over time that are sort of eventually glued together. It's kind of lacking coherency at times, which is why in additive NASA actually was proactive. We wrote an overarching document saying this is how you qualify any material, any process, and here are the requirements. Maybe everyone hates it because it's really prescriptive and very process control oriented. But it's an upfront level playing field that anyone, any business size, a small shop versus a major contractor, can get involved in. And for polymers or any of these specialty ones – I'd actually worked with Shane when he was at CalRAM on trying to get early work done on Inconel 625 – it's hard to find a lever to justify a particular decision. Unless you have an end user community screaming for something, moisture content, resin content, whatever. Unless you have a standards organization that comes in and says this is what we ought to do – we've learned this for other conventional materials processes – you want to do it like that. Or, you drive a flexible model where, when you look at say an anodization document, you might have multiple types and subtypes. Maybe you start looking to documents to have your feedstock conform to two or three different levels of quality and you have a generic one that's more broadscale production. Or you give yourself room to grow as you see a tighter control band needed for nuclear or aerospace or whatever your application is.

(Shane) I think that's fair. If you look at the early polymers, we had the UV curing polymer categories, material jetting, and vat photopolymerization. Those materials tend to absorb moisture and cross polymerize continuously. They don't make good production parts. Then, if you look at other types of polymers, it's changing now but generally they're not the class A or B or even C criticality parts that are produced. They're more in the C or D category. And so the requirements for standards are lower, generally speaking, when you have lower classification. But I see that changing quickly with these continuous fiber materials. The pekks, the peeks, the polykeytone and the ultem type materials are going to push polymers more and more into structural type applications and I think we're going to see a big need for standardization in that area.

**I'd like to think beyond just necessary components which we utilize to define materials in standards and specifications. It's a value chain that promotes the utility of additively manufactured products. Thinking**

**upstream of the AM process, does anyone feel that there are additional controls, which today are underutilized upstream for feedstock or precursor materials, in order to effectively source AM feedstocks of any type (metal, ceramic, composite, polymer)?**

(Isabella) I don't know if I can really answer your question but, for economic purposes, we are wanting to look at more continuous processes. Even if you need to do sintering, to do it either in-situ or at least continuously. By doing that, I think there might be some obviously different kinds of controls or evaluations necessary. Especially, if you do it in-situ and maybe not on the whole part simultaneously. That opens up a different value chain where different controls might be necessary

(Bill) When we talk about process controls, I believe there are at least three areas. We need to do a better job in understanding lot and how the material is melted and sourced. That becomes an issue when we have these continuous – we say recycling and reuse – machines which I believe is the future of additive. We've got to get up in terms of our production values. The second one is the whole issue of rheology and understanding flowability, particle size distribution, and so forth. I don't think we've really wrapped our minds around that. The third one is this whole idea of the change of composition as we process the materials and the reuse. So, in terms of oxygen pick up, carbon, the change, things that are potentially brittle. Carbon is not necessarily a good thing. So, understanding those control limits. And so there's a wide open area in terms of sourcing. Because powder is very heavy, we have them in what look like milk jugs. That's not a great way to industrialize the process. Then you have hazardous material handling, etc. So, this whole issue of containment, flammability, contamination of the powder, and so forth. So there's some real challenges to this whole industrialization process. Right now, I don't want to call it a cottage industry, but clearly it's craft. And we haven't really developed ourselves for high scale production. I think those are at least some of the upstream controls we need to focus on.

(Bryan) I think the other addendum to that is process modeling. That really fundamental, computational, material science at different length scale. NASA funded a three year study looking at non-equilibrium thermodynamics in super alloys to see, when you've got something that's going to have nine or ten primarily constituent alloys, what are you going to form with a tail? What is your nitrogen and your carbon going to do if you've got a niobium, or an iron, or nickel, or cobalt, all these things in a single alloy? Tied to that as well is looking at your processes and trying to do a more realistic process modeling of how the individual processes are going to affect your powder. As more machines come on the market, with more variants or upgraded software, trying to see if you can have a constitutive modeling approach that takes you from your feedstock and can pull in different elements of this. That's something that actually has to be government funded. Because it's not easy and you want to get it across machine classes to basically say, if I want to start with this can I have some idea of what might come out at the end, or that would drive my design of experiments? I think that gets back to the point that Teresa and Ellie made earlier about conversations with suppliers. If you can be doing some of that and kind of pointing to this is what we think we need, then you can drive the market towards the solution earlier without them having to invest heavy infrastructure in a process that might not quite make what you're looking for, has unsatisfactory material that has to be scrapped, etc. The modeling part is something that I think we don't necessarily look at as much for standards. But I think it's an underserved area because we can see that it actually could lead to better iterations, time, and savings for everyone.

(Igor) It also comes up at least in ceramics to breaching the microscopic modeling at the particulate level. And how that translates into the continuing modeling of the rest of the process. I think something that is missing is they really stop at the particular level of your feedstock material and then follow it through.

**There's a question here from the audience. I assume at this organization they're encountering a deeper understanding of how different equipment designs require select modifications to certain characteristics of the feedstock that they're utilizing. The question is: Is that a common problem across the spectrum with AM technologies?**

(Shane) If you look at the main architecture of powder bed fusion, there are two types of feed mechanisms. One is a piston driven mechanism that raises the powder up and then the spreader – the recoater we call it – brings it over the part bed. The other method brings the powder from the top and the powder comes down, and then it's deposited across the build platform. Those two methods require a different flow characteristic of the

powder. That was early on of the top feed as they were being released, those machine architectures, the powder generally had to be changed in the particle size distribution upward to get it to flow better to be able to operate in that environment. There are other aspects to multi laser systems that are going to become more and more obvious with respect to process gas flow which is a critical parameter of the process. As the machines get larger, that's going to be more difficult to manage and will require a different aspect of powder spreading and feedstock control.

**A follow on question to that asks: Do specifications then need to address the interface of compatibility?**

(Shane) The way we're looking at it in ASTM is that if you start to try to specify a particle size distribution, for example, for every machine model and manufacturer that comes out, that would be ridiculous. So, what we are looking at is that we have a specification around the IQ OQ PQ process, which means that you understand your initial quality, then your process characteristics, and then your end part. Through that process, you would determine what your inputs are that affect the process. Because additive is a special process. When you know those inputs, then you characterize your feedstock so that you remain within your process window. That's a better way to look at it from a risk-based management perspective than a prescriptive attribute to the feedstock itself.

(Bill) We also have guidelines on installation qualification from a machine standpoint that we've been working on and we're in the process of publishing. In terms of the powder, we have guidelines in terms of classes and the particle size distribution. Typically, in general, smaller powders on the order of 15 to 20 microns are used in binder jetting. For powder bed fusion on the order of 40 to 50 microns at least for aerospace. And then larger diameter powders in terms of directed energy deposition on the order of 80 to 120 microns. So, we have to set up the classes. We've talked about tying this originally to the different machine modalities and then realizing that there could be overlap, depending on application. What we're trying to do, as we move forward to standardize, is we're trying to take these snapshots in time. Realizing that we're supposed to anticipate being forward looking and not being overly constraining in some of the recommendations or the guidelines that we're putting in place. What we're trying to do is afford that flexibility as well enable broadspread adoption of our standards. It's a trade-off.

(Shane) If you look at the electron beam melting process, usually they use 50 to 100 microns in that range. So it's a powder bed fusion process, but a larger particle size distribution. Laser, it's more like 15 to 45 microns or 20 to 63. So they are significantly different, although they're both powder bed fusion. So it's really difficult to categorize one type of powder for a particular modality. And then we have other systems that are going to spread the powder without any contact to the powder bed itself. And that may require a different particle size distribution. But the processes themselves of powder bed are fairly forgiving. The process windows are fairly large. As long as you qualify something and your powder source doesn't change, you're usually in good shape.

**We mentioned a lot of variables in terms of attributes of powder feedstocks. How much consideration goes into standards development when you start to think about processing limitations? The physical limits of, say, the metals, or the polymer, or composite supply chain to readily produce something to meet your needs? And, furthermore, the consequence that bears on being able to readily source things you need, particularly concerning scarcity of resources? Does that go into standards development or the creation of the content within?**

(Bryan) Yes, when we write internal standards, we have to address that all the time. Particularly, if you're going to a specialty material. For example, if you want to get C103, you know that there is an extremely limited supply base. Particularly, if you can only use domestic suppliers, there may be only one or two. And it behooves you to understand what is their capacity. Do they have pilot plants versus full scale production plants? This is true for both conventional forming processes or powder specific to additive. We run the risk of over specifying or driving our costs up to where it's stratospheric, but we're willing to pay a fair amount per pound if we can get it for a limited basis. But when you're doing it properly, and that was true when I was in industry at Rocketdyne, we would look across alloy systems or ceramics or whatever we were using. What's this going to do? Do you have an understanding of what your supplier base can give? How robust are those suppliers? Because if I'm dealing with a small shop that's just coming up to speed, are they going to be able to deliver? What are the growing



pains that are going to be endemic? Versus I'm buying from a major established producer that's delivering by the kiloton a year or by the week even. You have to take that into account, particularly if you're going to write something tighter than what they're offering. That should be a very early consideration. I guess that goes back to the earlier point about communication. I think it's also communication and understanding what exists within the domestic and international supply chain that's robust. And I think we've all learned that lesson over the last year and a half about paying more attention to your supply chain.

(Eliana) I have a word about C103 in particular. That's one of those materials that really only has a certain particular end use, and it's really constrained because literally only I think two people make it in the U.S. or North America. If you are trying to get it for AM purposes, you are competing with traditional product. I'll go back to the designers of the intended parts. When they send out the request for a quote, they need to understand that lead time isn't just because it's AM or an AM feedstock. It's coming from the same place as it would for a traditional product. Maybe that's what we also need to educate our designers and the people making these parts. If you want to use AM or you want to use traditional, it's all coming from same place.

(Shane) Earlier this morning, I showed a standard in development on the niobium-halfniium—that's the C103 alloy. This is one material where you can print the part and you have a cost advantage over traditional manufacturing of machining right out of the gate. It's about one third the cost. There are specific space applications where this is used pretty extensively so we don't have to design for additive. You don't have to take advantage of part count integration. You just print what it was you were machining and you can save 60% of the cost. This is one area that is bound to expand. And if there are more uses of this powder, which costs upwards of 750 dollars a pound, then there will be other manufacturers that will get on board. Right now the use is very limited because processing it in powder bed fusion is extremely tricky to keep the chemistry the same.

(Bryan) The problem is with some of these niche materials going to additive. If you have a better buy fly ratio for your given part, while it benefits your organization, there's not necessarily the long-term benefit to that organization, because you're not going to go make more thrusters or heat shields or other things with a C103. Instead of buying ten 10 pounds of material to make one, you're buying three to make one. There's going to be a consideration with choke points. What's better for you or the industry might not be better for that given supplier. It's going to be challenging. Some of these are going to be hard industries to have new competitors break into. There's not a small cost of entry so that is one of the concerns. If you look at, say, ceramic matrix composites, the fibers used in those, it's the same thing and that's internationally. There's only a few suppliers. I just think that we have to be a little cautious because sometimes those suppliers don't want to do that. They might want to actually sell you the part instead because they don't want to give you the powder because otherwise it's a diminution of their business space to an extent where they're selling less product or at a lower margin.

**I'm thinking about as you get the powder into your facility, you go to start using it, and even before it shows up, how it gets to you. So, packaging, handling, reuse – we've heard a bit about safety today. I think Shane's mentioned now three times moving some of these materials that can feature safety considerations. Are there opportunities to do more to effectively utilize feedstock materials, or keep people safe, or make us more successful whenever we process with them, in standards?**

(Shane) The one thing I agreed with Bill on earlier is that the large machines are definitely going to require a different approach to both powder reuse and powder acquisition and the method that the powder gets from the atomizer to the facility that's processing it. I think in the future we're going to see more large-scale integration, vertical integration of atomization, and powder use where what you don't use gets recycled easily back into the process. But this whole concept of powder evolution, or changing in the build chamber, because of either oxygen that gets attached to it, or moisture that gets on the powder, all that will be mitigated by vessels that go from the atomization where the powder is filled under inert conditions, all the way to where it goes inside the machine under inert conditions and the machine has a very low oxygen level. That is a model that's being worked out right now and will happen. When you have machines that hold more than a ton of material, when you're making parts that weigh 3 or 400 pounds apiece, you have to think of it in a different way than we have been making little fuel nozzle tips that weigh a few grams.

**Would folks on the panel agree that there are similar considerations to what just Shane outlined for ceramics and polymers and composites?**

(Igor) With ceramics, you have to think about final shelf life. It may have to be used on the same date. That presents a challenge.

(Eliana) We have to think about different ways in which we handle, store, transport, and reuse powder. One of the really amazing things about AM is we're going down a path where human interaction is minimized, especially during powder handling. If we can get that concept of leaving humans to do more of the higher forming tasks, that is the concept of the factory of the future where you have machines making other machines. At Relativity Space we called the WAAM process Stargate. It was named after a character from a video game which is a machine that builds other machines. All of those defects or contamination or anything that's brought in from the outside environment which could potentially cause a defect, you can try and minimize some of those things in making improvements in the whole process. As was said, storage, handling, shipping, what do people do with their failed builds? How do you recycle those? I think that's a great topic for a future panel on the advantages of using AM.

(Bill) I think this is an example of looking to other industries for best practice. Pharmaceuticals is probably the best at managing powders. Any particle that's small enough is potentially combustible. I was in Wichita years ago when we had a grain elevator that exploded. It was 30 or 40 miles away and it was like TNT, just phenomenal. I think that's the other thing that we haven't really wrapped our minds around is this whole industrialization process. If we are going to stay the course with regards to powder bed fusion and directed energy deposition powder systems, we've really got to go beyond small batch handling. It's a huge barrier at the moment.

(Teresa) I think this really does fit into the whole standardization scheme. If there is a vessel that the atomizers can put the powder in that then flips onto any of these different machines' feedstock port, that's what we want. We want a standard. A standardization process gives you a way you can work together within all of the legalities of working with your competitors and also come up with something that is the best for the industry.

**We have a member of the audience that has a question as follows: Regarding shelf life of the powder, it's my experience over the years of dealing with powdered metals that when you add chromium, nickel, or any of the heavier metals, and you mix it, you've got a shelf life of a certain time that you have to process that material, or it starts to segregate. Do we address that?**

(Shane) In powder bed fusion our materials are pre-alloy. The particle size distribution changes when you ship or shake it up but, once you sieve the powder, you pretty much make it homogeneous again. But that's a good question. Bryan talked about invar before as one of those binary materials of iron and nickel. We have a lot of upside to be able to dry blend those powders and make invar. If that works appropriately, then we're alloying in the melt pool of the powder bed fusion process. And if that works, then you extrapolate that out. Most of the materials we print today are less than 20 elements. You can have 20 elements and blends dry blending your powder and go from titanium to nickel in a relatively short amount of time. So there's a lot of upside to that. I think a lot of research needs to go into the dry blending of alloys and what particle size of the powder you'd have to get in order to make that work.

**I had a question that I had shared with the panel ahead of time and it asked how we felt that standards for feedstock or precursor materials could address the need to foster rapid vendor qualification. I think we've hit on a number of things here in this second session. Along those lines, though, I want to ask the question are there new work models or untapped opportunities to engage with people or something else altogether that standards development organizations need to consider to adopt that will foster addressing these needs? What else could we be doing?**

(Shane) ASTM is considering having a certification program for suppliers of AM materials. If you had an ASTM certification as a material supplier, you would then have an accelerated path toward adoption.

(Teresa) I think that same sort of thing is at work with ASME. If you're working in the nuclear field, you have to have an ASME nuclear certificate as a raw materials supplier. So someone who's providing powder or welding wire to a nuclear application would have to be audited and certified to do so. I think that should be a first step to entry. I don't think it's a problem getting into your supplier's business. It's your business that they have a good quality system. I think that's a very reasonable barrier to entry.

(Bill) From an SAE standpoint, we haven't focused so much on the vendors in terms of specificity in regulations and guidelines. I think what we're looking at is trying to reduce cost. Within the last year and a half, we launched the AMDC, the data consortium, because at the end of the day aerospace is empirically grounded. And we need these data to be able to point to in terms of design guidelines. And right now, if you look at, let's say MMPDS, there's hundreds and hundreds of pages in their volume of the metals handbook that addresses metals, but there's only three instances of additive manufacturing materials that are in the process of being included in that. And clearly that isn't good enough. So we're working on different materials to put that out in the public domain to help standardize that too. I think it's a huge area of need. And CMH-17 is doing this as well working with the non-metals. As we push that data out there, and we develop some understanding behind the chemistry and whatever the processes to get these data in the handbook, then that will drive its own adoption too. It really comes back to the market. If the demand is there, we'll figure out a path forward even from a sole source standpoint or pushing through standards and trying to make this more of a commodity and have some type of volume approach for a broader market.

**Along those lines, we talk about research and we talk about standardization. Are there different things that we need to be working on to get the most utility from both, or are they one and the same?**

(Isabella) I personally think it should be closer to data. We are doing the research already not only on the industrialization, but optimization, qualification, and standardization for the use of AM. Especially in our industry, you don't have a lot of small variations in material specifications. You can understand what needs to be standardized so that you get to your different end processes.

**Do we think that there is an opportunity to better focus the research community to help foster the development of standards?**

(Shane) That's the reason that the Center of Excellence was founded. When AMSC put together the first roadmap, we had a lot of gaps that needed to be filled. F42 looked at those gaps and determined that they could not be filled without some fundamental research to understand what powder recycling is like, to understand how the material properties evolve with the microstructure, to understand some fundamentals of science and how the models integrate with what happens in the process. So that's the whole reason for the ASTM COE. For a project to get approved, it has to fill one of the gaps that was identified by the AMSC and a standard has to come out from that research. So my feeling is, yes, we need more research. The Center of Excellence is doing a great job, but more research would be better.

(Isabella) How do we ensure that we keep our gap analysis up-to-date with other information that may come from other sources? It was mentioned before to make information available sooner.

(Shane) That's a really good point because we had gaps that were at a moment in time which is now getting to be four, maybe five, years ago when we first sat down and started to identify that. In that time, the machine architectures we're using for additive manufacturing have evolved. So, to some extent, those gaps aren't necessarily existing the way they were when we originally sat down. And we've also created standards to fill those gaps. So, I think we really need to focus on keeping that up-to-date and, as the industry evolves, keep updating what those gaps need to be.

(Bill) Thinking about the question a bit more philosophically, there has to be a business model behind research as well. There has to be some type of return. In the academic world, the return is publications typically and some thought leadership and a certain amount of prestige that goes with publishing in these journals. But I think that nowadays we realize the research has to be more applied. And the government is funding significantly less of that. So that burden or opportunity shifts to industry. I think that creates a need for

consortia or at the national labs. It would be interesting to see how their incentives vary as they move forward to create standards. I think standards are problematic for two reasons with low TRL. One, because you don't know what you're standardizing, because you're researching. You don't know what you don't know. But, number two, what you do know sometimes you don't necessarily want to make public until you can wrap your mind around that and package that such that you get the benefit of developing that intellectual property. That's the trade-off. And then standards are needed when you see that there's a large enough market to justify the energy to go in and standardize the process. Realize that typical standards take at least two years to develop, at least in terms of aerospace, where there's a certain amount of rigor that's required. So these are huge investments in not only time but human capital as well.

**To help encourage people to think about getting engaged, how hard is it to amend a standard and get that to the public? If you don't get your voice heard the first go round, is that an easy thing to do or a hard thing to do?**

(Isabella) My perception is that it is a hard thing but I do not necessarily have the right experience to talk about that. So I'd like to hear from my colleagues.

(Bill) I could speak briefly anecdotally. We've got twenty-one standards that are released. We have three that have been amended or revised. Even that revision process, even though you have that initial consensus, it's a model. So, in this framework, we have an idea based on the author's. Even though this is diverse, we believe representative of the supply chain, you really don't know until you implement that. There's nuances and semantics in terms of what's being interpreted. There's a certain amount of subjectivity in the application of the standard. Usually you need a couple of years in the field to get feedback and that's fed back into the committee. But I think that consortia, ASTM, ASME, we're all very similar. The real challenge is getting the sponsor. The sponsor is somebody who has a fundamental interest, bandwidth, and competence to be able to champion this. And I think that's the secret — to get a sponsor across the goal line regardless if it's new or a revision. I assume, Shane, that you guys have the same challenges.

(Shane) Yes, with the exception that if it's a fairly minor change, you only ballot the change; you don't have to ballot the entire document. Every six years we have to re-ballot the document. That's just the normal ASTM process to keep it current. But if there are wanted changes within an existing standard, we only ballot the changes. The entire document is not opened up again. The reason why that can be problematic is that the ASTM F42 membership continues to grow. As I said this morning, there's over a 1,000 members. A new member could come along and one negative vote on a ballot stops the whole process. What's good about only balloting the change is that's the only thing up for review. In the worst case, you revert back to the way the standard was originally written.

(Teresa) I see a lot of what you're saying that a new standard typically after about two years is ripe for some revision. Because you learn how it's actually applied in the industry. As they get more mature, the revision cycles change, and they might be once every five years. Key to it is that sponsor. And getting people that are actually interested in doing standardization work. I mean this is not the most exciting stuff in the world. I think the idea of making the people who are actually making money off of it, whether it's the suppliers or the parts producers, recognize that their voice can be heard and what their stake is in it, it works out for the best of the industry. What I was told thirty years ago, when I started doing committee work, is don't worry about anything that Lincoln Electric has or doesn't have in their product portfolio, or how this will impact them. If it's good for the welding industry, it's good for Lincoln Electric. I think we all need to kind of step back and say, if I can make some change that's good for the additive industry, it's good for everybody in the long run. But it's a really tough thing to foster.

**The last question I want to ask each of you. It pertains to where we are today versus the AMSC standardization roadmap that tells us what we should work on. Is the roadmap an accurate depiction of what we really need? Is there a major gap in the standardization landscape right now? Are you happy with where things are going?**

(Bryan) I think there's a gap and it's a combination of a number of the factors that were brought up today. We need to think about the materials we have now and what we're going to have with the new machines in the next few years. We need to do a gap analysis and figure out where we need to get smarter.

(Igor) There is a gap with regard to ceramics. We need to understand what the needs are. In ASTM there is a group now formed to evaluate this issue with regards to feedstock characterization looking at where things stand and what's needed. We need to talk about what's available in existing standards and what needs to be modified to adapt to ceramics.

(Isabella) There are a lot of opportunities for us and really thinking potentially very far in the future. My wish is really for us to have working models that are material and process agnostic. So that we can be more competitive moving forward.

(Teresa) I think in general it's absolutely necessary to have that broad brush these are what our gaps are. But I'd also like to see some sort of weighting put on these gaps because there is more or less an urgency to some of them in terms of commercialization.

(Bill) I think in general it's an excellent document and I commend you all for taking the initiative to pull this together and maintaining it. I think you guys have done a great job. I think from our standpoint the gaps are in the area of testing and inspection. Typically, you print things that you can't machine easily. These don't x-ray very easily either. Now, when you have these lattice structures, what are you looking at? Where do you CT scan some of this? I know we're doing some research in that at the industry level, but I think that's an area that we could improve. And the other one would be modeling of course. That we talked about but that's a deep well.

(Eliana) I think standards need to be more inclusive. What I mean by inclusive is that it incorporates the interests of what people are looking for to guide them for manufacturing and so forth. But also people have to get involved. I'll give you an example. In the last four weeks I've had at least two very young, junior engineers send me a message out of nowhere from the new space companies. They asked whether they should join F42. I said yes because you need to have your voice heard. If these standards are written and you're not part of it, you're not a part of it. It doesn't matter that you're junior in the company, or young at your job, or just learning. That's how you learn. That's how you participate. Specifically, in F42 where there's a spaceflight sub group. Everyone's talking about space. These people are coming in with new ideas and new processes and things they want to do. Their voices should be heard. So, from my point of view, anything that standards committees can do, whether it's ASTM, SAE, AWS, or anybody else, should try to be more inclusive of that.

(Shane) Speaking of space, I don't think they've heard that the TRL level of additive is only three or four. I think they think it's much higher than that. I think the AMSC roadmap has its roots in a meeting that I helped organize at Penn State with a 3D center there. I was happy to participate in developing the roadmap at least on the metal powder bed fusion side. I agree that it was a landmark work and it continues to evolve in the right ways. What I would like to see more effort put on is the in-situ monitoring. Because that area really wasn't well developed at the time that we started to work on that as it is today.

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Brandon Ribic thanked the attendees and the panelists for their participation, noting he really appreciated their time and perspectives.

#### **Closing Remarks**

Jim McCabe added his thanks to everyone, especially Brandon Ribic for facilitating the panel discussion and for taking the pulse of the group on where we are and where we need to go. It was good to hear the call for more participation. The SDOs are always in need of more volunteers from the user community as well as from the manufacturing community to get these standards written. A meeting report will be prepared to capture key points. This type of discussion is really helpful toward the evolution of the AMSC roadmap. It's great to hear that

it's a foundational document for the R&D efforts that are underway, while acknowledging that the technology is changing and we may need to reevaluate where we are and what we need to look at going forward. We will be sending out the presentations. If you know of others who didn't get a chance to participate today, please direct them to [www.ansi.org/amsc](http://www.ansi.org/amsc) or have them email [amsc@ansi.org](mailto:amsc@ansi.org) and we'll put them on distribution list.

Brandon Ribic thanked the speakers and Jim McCabe for his role in organizing today's event, adding that we look forward to our next event soon.